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A comparison of some aspects of sedimentation and translational tectonics from the Gulf of California and the Mesozoic Tethys, Northern Penninic Margin[1])

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ABSTRACT

This paper draws attention to aspects of the modern, obliquely-rifted Gulf of California which can serve as an actualistic process model for a translational regime in the Penninic corridor of the Mesozoic Tethys between the Adria-Apulia and European margins. The regional scale, complexly faulted bathymetry and mechanism of formation of oceanic crust are thought similar. Deep Sea Drilling (Leg 64) in the Guaymas Basin penetrated sequences of redeposited hemipelagic muds which are intruded by multiple, tholeiitic dolerite sills that also caused local hydrothermal metamorphism within the young sediments. These features are compared with the Bündnerschiefer facies of the Northern Penninic Valais Trough which have metamorphosed, but concordantly intercalated prasinite (tholeiitic) bodies showing contact features. Bündnerschiefer is interpreted as a combination of hemipelagic drape and redeposits in a broad slope and slope-basin setting including areas of local ocean spreading. In a preorogenic Gulf-of-California-type setting, separate elements of an ophiolite complex may be emplaced in close proximity and at similar topographic levels. The implications of the actualistic model are applied in a preliminary, hypothetical three-stage evolution of the Northern Pennine Zone.

ZUSAMMENFASSUNG

Geologische Aspekte des heutigen Golfs von Kalifornien können als aktualistisches Modell für Teilgebiete des östlichen und nördlichen penninischen Faziesgürtels der mesozoischen Tethys herangezogen werden. Grösse, Morphologie, komplizierte laterale Bruchtektonik und Bildungsprozesse ozeanischer Kruste zeigen Ähnlichkeiten. Bohrungen der DSDP Leg 64 stiessen auf mächtige, kalkfossilienarme, feinkörnige, hemipelagische Sedimente mit spärlichen Kalkfossilien. Der Transport in die schmalen Becken erfolgte zumeist in Form von Trübeströmen. Pilzartige tholeiitische Intrusionen durchziehen in mehreren Stockwerken die wasserreichen jungen Sedimente und verursachten in lokaler Metasomatose Mineralparagenesen der Grünschieferfazies. Vor allem die Bündnerschiefer aus dem Wallisertrog mit ihren konkordant eingelagerten Prasiniten werden einem ähnlichen Ablagerungsraum, einer breiten Hang- und Hang-Becken-Fazies, zugeordnet. Der Golf von Kalifornien illustriert auch, wie vor einer Orogenese Elemente eines Ophiolith-Komplexes in einer axenschiefen Translationszone nebeneinander und nicht wie im klassischen Modell übereinander auftreten können. Aus den Analogien zum nordpenninischen Ablagerungsraum wurde eine hypothetische, dreiphasige Entwicklungsgeschichte abgeleitet.

Introduction

Paleogeographic evidence has been discussed in a number of recent syntheses which indicate some form of major strike-slip and transform lateral movements

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along the Pennine realm of the Middle Jurassic to Middle Cretaceous Tethys (e.g. TRÜMPY 1975b; LAUBSCHER 1975; BOURBON et al. 1977; BIJU-DUVAL et al. 1977; HOMEWOOD 1977; LAUBSCHER & BERNOULLI 1977; BERNOULLI et al. 1979; GEYSSANT 1980; LEMOINE 1980). Some aspects of ophiolites, ophicalcites and related rocks have also been linked to possible transform faults along a relatively narrow belt of oceanic crust connecting the Ligurian with the Dinaride regions (DIETRICH 1976; LEMOINE 1980). As pointed out by BOURBON et al. (1977) movements along the translational margin of an oceanic area, for instance parallel to the Briançonnais Swell, should be expected to produce a more complex bathymetry than a passive margin. As a consequence of the Alpine deformations, most pieces of the paleogeographic puzzle are jumbled such that we commonly turn to actualistic models to help visualize the Tethyan environments. Details of translational margins in oceanic settings are poorly known but the Gulf of California is one such area. The recent Deep Sea Drilling cruise (Leg 64) into the Gulf of California has now made a major contribution to our understanding of the sedimentation, tectonics and formation of ocean crust in obliquely-rifted young oceans (CURRAY, MOORE et al. 1979; EINSELE et al. 1980; CURRAY, MOORE et al., in press). The purpose of this communication is to discuss some implications of such an analogy which might apply to the Penninic areas of the Tethys. This analogy leads to some new perspectives on the importance of oblique-rifting for slope-basin sedimentation, subsidence, ophiolites, breccias, ribbon continents and early metamorphism. Some differences in the nature of ocean crust can be explained by the sedimentation rates in such regions. A comparison with the hemipelagic setting of the Gulf of California can be used for a broad deductive approach for interpreting the paleoenvironment of Bündnerschiefer (Schistes lustrés) sediments.

Actualistic models are not identical with their ancient analogs but can inspire alternative approaches for fieldwork. Many of my specific comparisons of sedimentation are aimed at the Bündnerschiefer deposits of Eastern Switzerland but some implications on the tectonics can apply to more "truly oceanic" areas of the Southern Piemont units (Platta Nappe, Arosa Zone). It must be kept in mind that the Gulf of California is a young (4 m.y.) oceanic basin (MOORE 1973) in an arid, terrigenous sediment environment; without the broad, epeiric seas which flanked the Pennine realm. It is this hemipelagic setting which provides some insights for the depositional environment of Bündnerschiefer in the Northern Pennine Zone, whereas the pelagic sediments which characterize the Southern Piemont belt are more similar to the situation on the East Pacific Rise junction at the mouth of the Gulf.

Terminology in this paper follows TRÜMPY (1960, 1980) whereby the Pennine realm refers to an essentially complex oceanic domain between the European and Adriatic continental margins. It is subdivided into the Valais belt in the north and Piemont belt in the south by the Briançonnais Swell. Thick Bündnerschiefer sediments are considered to occur mostly within the Valais belt and along the southern margin of the Briançonnais (Avers, Combin). A point of controversy seems to be the nature of crust along the Valais belt, which is considered to be rifted into a thinned continental crust. Northern Pennine as used here refers to the general depositional area for Bündnerschiefer and includes both the Valais belt and northern parts of the Piemont (Fig. 1C). Ophiolitoids (sills, basalts, prasinites intercalated with Bündnerschiefer) occur widespread in the Northern Pennine units from the Western Alps to the Tauern window. Although Schistes lustrés is a more common designation for shales of the Pennine nappes; I prefer to retain the synonym "Bündnerschiefer" to indicate the emphasis on sequences exposed in Eastern Switzerland.

The Bündnerschiefer problem

The extent and depositional environment of the Mesozoic Pennine Sea is represented by a question mark on many palinspastic reconstructions. There are several reasons for this: Bündnerschiefer are critical sediments in the North Penninic realm but the complex, seemingly monotonous, gray mass of slightly metamorphic, calci-schists, limestones and shales which comprise the Bündnerschiefer formations of Eastern Switzerland have excited only a few adventurous field geologists. These studies, however, report a much more differentiated rock assemblage than given by first impressions (cf. HEIM 1921; NÄNNY 1948; JÄCKLI 1941; NABHOLZ 1945; KUPFERSCHMID 1977; PROBST 1980; BOLLI et al. 1980). Extensive deformation, facies changes, metamorphic grade, poor outcrop conditions and lack of fossils hampered any compilation of a detailed stratigraphy. The Bündnerschiefer was merely defined as deposits in the Northern Penninic Zone between the Liassic formations and Cenomanian Flysch (e.g. BOLLI & NABHOLZ 1959).

With the advent of plate tectonics theory, Atlantic-type spreading models ascribed Penninic ophiolites to an orthogonal spreading ridge, which implied a vast oceanic portion of the Tethys which opened from Early Jurassic through Lower Cretaceous, and was subsequently subducted from the Late Cretaceous onwards (DEWEY et al. 1973; DERCOURT 1972; DIETRICH 1976; GEYSSANT 1980). A shift from passive to active margin is implicit. The present outcrops thus represent only a few random, disjointed remnants of ocean crust and oceanic sediment caught between microcontinents or Eurasia and Africa. With most of the evidence missing, this melange scenario leaves little hope for unraveling the stratigraphy. Recently, palynological dating has led to a major breakthrough (PANTIĆ & GANSSER 1977; PANTIĆ & ISLER 1978; BOLLI et al. 1980). Age assignments, at least in the Northern Penninic Zone, show more coherency within the Bündnerschiefer sequences than hitherto believed.

Scale

There is little agreement on the width of various Penninic basins. Some authors, while accepting a plate tectonics approach have hedged misgivings for a broad depositional realm, in more easterly parts, stressing instead reconstructions with narrow zones of oceanic crust (e.g. TRÜMPY 1975b, 1976; BERNOULLI & LEMOINE 1980; BOURBON et al. 1977; GEYSSANT 1980). Even in more expansive reconstructions (Fig. 1B), the amount of oceanic crustal area portrayed is very close to the amount of young oceanic crust estimated for the Gulf of California. Compared with Atlantic-type spreading ridges or Pacific back-arc marginal basins, the area underlain by Valais and Eastern Piemont units may have been an order of magnitude smaller. Figure 1 graphically shows the situation and oceanic crustal area of the

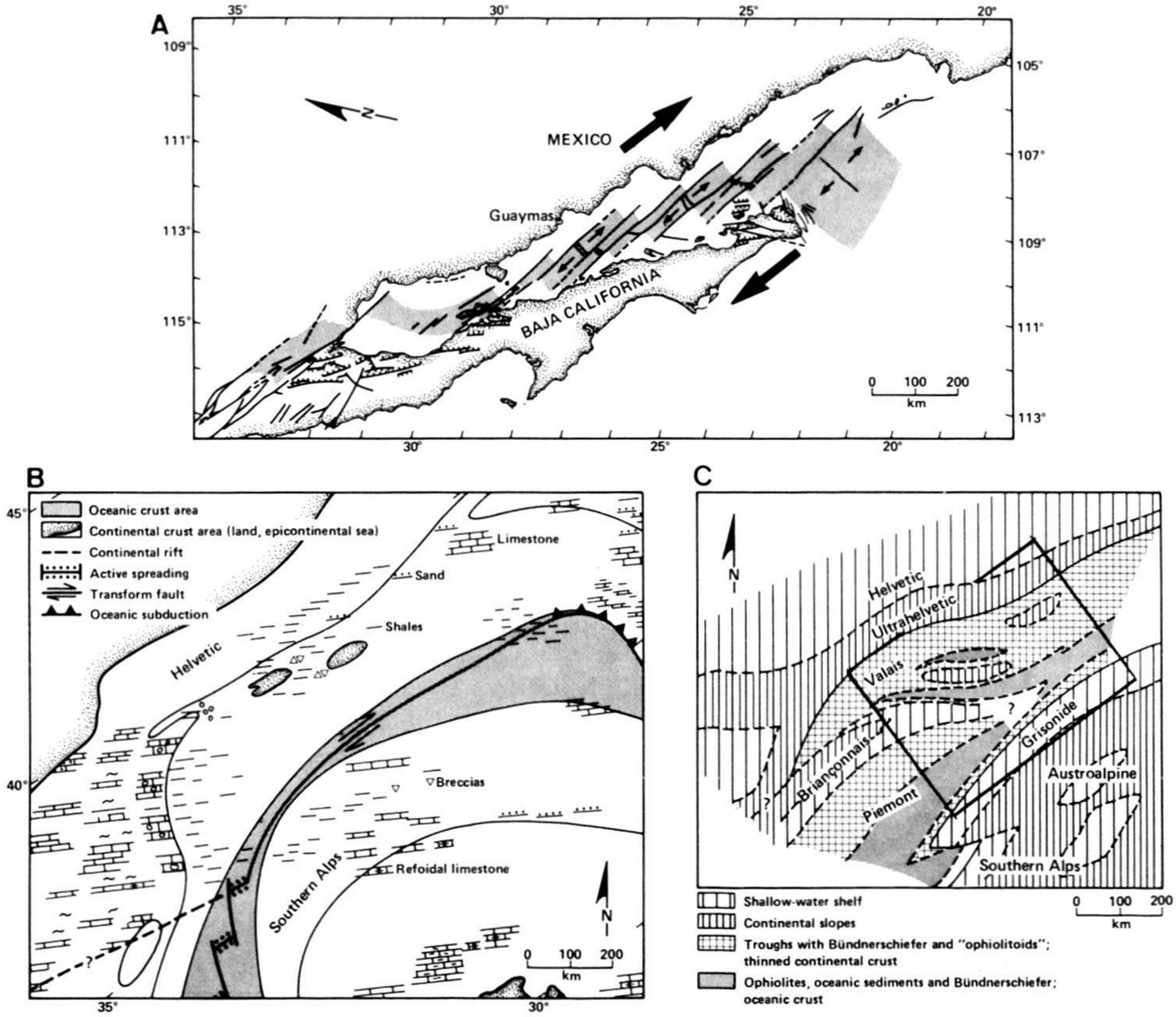

Fig. 1. Same-scale comparison of the present Gulf of California (A) with two popular reconstructions of the middle Mesozoic Alpine Tethys Ocean. A: Oblique rifting in the Gulf of California after Moore (1973) with young ocean crust and spreading centers (stipped area) between transform faults. B: Biju-Duval et al. (1977) for the Dogger implies strike-slip in a broad Southern Pennine area. C: Trümpy (1980) implies translational movements for lowermost Cretaceous. Inset rectangle covers the approximate area considered for this paper.

Gulf of California and compares this at the same-scale reproduction of two frequently-cited paleogeographic reconstructions of the Alpine Tethys during the Late Jurassic (Biju-Duval et al. 1977; Trümpy 1980). Both also imply translational tectonics.

Setting of the Gulf of California

Although their scale and paleotectonic setting may have much in common, the Penninic Ocean and the Gulf of California differ in important paleoceanographical and paleoclimatological aspects. A major difference is that the Pennine realm had an E–W orientation and was flanked by broad low relief epicontinental or epeiric seas with widespread shallow water carbonate deposition. The Gulf of California is situated in an arid region flanked to the east by a broad clastic piedmont with only a few perennial rivers. The Cordilleran backbone of the Baja Peninsula tilts assymetrically towards the Pacific Ocean, leaving the Gulf side formed by rather abrupt scarps, without larger perennial rivers. Most of the sediment is thus derived from the east, transported by seasonal sheet floods and is generally clastic. Keeping this important difference in view there remain several points of comparison.

The Gulf of California is roughly 1300 km long and between 100 and 250 km wide. The most prominent morphological features are the series of semi-isolated, relatively small basins, which are linked en echelon by steep faults. Most of the seafloor area is dominated by slope settings, whereas offshore banks and isolated ridges are quite common (cf. Fig. 1A and 2; RUSNAK et al. 1964; BISCHOFF & NIEMITZ 1980). The basins deepen from 600 m in the north to over 3000 m toward the south. They are interpreted as sites of active spreading centers (LARSEN et al. 1968). Curiously, these spreading centers remain the deepest point of the basins because the rate of rifting (6 cm/year) is still considerably greater than the rate of terrigenous and diatomaceous sediment input (1-2 mm/year). This leads to a dynamic corrolary that once rifting is initiated between continental blocks, the depressions formed will persist without filling as long as spreading continues (SHARMAN 1976; EINSELE, in press).

The Gulf of California is a very young ocean basin. Although bathyal marine sediments are known from an earlier "protogulf" stage of basin history (MOORE 1973; KARIG & JENSKY 1972), the initiation of oblique spreading and formation of ocean crust seems to have been initiated about 4 m.y. ago (LARSEN et al. 1968; CURRAY, MOORE et al. 1979). Since then spreading has proceeded at rates around 6 cm/year for a total of 240 km separation. However, the oblique component of this movement implies that the basin has widened orthogonally less than 75 km. An application of this analogy to the Penninic Sea might suggest how, in spite of up to 2000 km of possible lateral movement (DEWEY et al. 1973) we need only postulate a translational Mesozoic oceanic region of about 200 km width in the N-S transect between Apulia and the European Margin (cf. BERNOULLI & LEMOINE 1980). Mesozoic translational processes may have lasted up to 65 m.y. (approximately 165 m.y. to 100 m.y.) and spreading rates of 2-3 cm/year have been suggested (BIJU-DUVAL et al. 1977), although new ocean crust need not have been produced during the entire period.

Morphology

A closer look at the Guaymas Basin region of the central part of the Gulf of California (Fig. 2) shows numerous features which might apply to a comparison with the North Penninic (Valais) Basin. Again we note that the scale of these features closely approximates palinspastic reconstructions of the equivalent Pennine facies realm.

Most of the Guaymas region comprises low angle, to steeply inclined slopes. These are commonly asymmetric; broad along the eastern margin and narrow along the western margin. Present day basin plains are comparatively narrow, small troughs flanked by low angle aprons. These basins include the North and South Rifts of the Guaymas Basin, and the Salsipuedes Canal and Delfin Rift Basins which are receiving terrigenous influxes from large mainland deltas of the Colorado

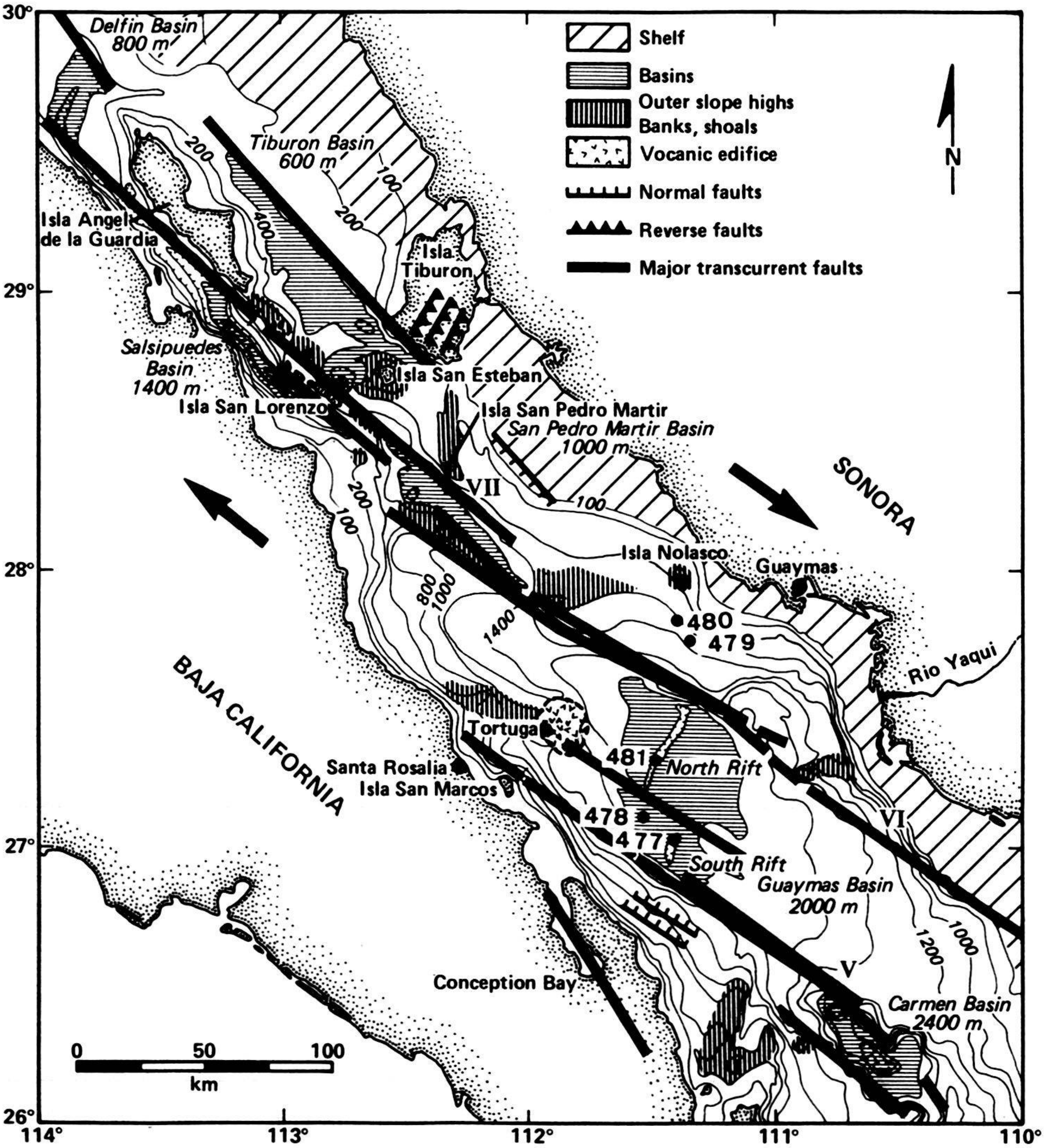

Fig. 2. Morphology and tectonic setting of the Central Gulf of California region with the 2000 m deep Guaymas Basin and surrounding areas and showing Leg 64 DSDP drill sites. The North and South Rifts form the current basinal lows; have high heat flows and are considered sites of recently active spreading. Note occurrence of numerous outer slope basins, offshore ridges and banks and the Isla Angel de la Guardia ridge; a continental fragment separated from Baja by oceanic crust and a recent transform in the Salsipuedes channels. Major transforms are labeled after MOORE (1973). Bathymetry in meters with a 200 m contour interval. Note predominance of slope environments. (Bathymetry after BISCHOFF & NIEMITZ 1980.)

and Yaqui river systems. In addition, there are also moderately isolated basins perched along the slopes, such as the San Pedro Martir Basin, Tiburon Basin and San Esteban Basin. These serve as catchment for locally derived components. Seismic profiles (MOORE 1973; BISCHOFF & HENYEY 1974) indicate the presence of numerous other fault-controlled slope basins, which are now mostly buried, but which have served as efficient sediment traps at some time. Some include thick, discordant and deformed packages from the "protogulf" series (KARIG & JENSKY 1972).

Several subaqueous ridges occur as prongs from the margins (e.g. near Santa Rosalia or Guaymas) or as offshore banks, or outer slope highs which are isolated from terrigenous influx. Many of these swells intersect with a water mass of low oxygen content and are slowly accumulating laminated pelagic diatom oozes (CALVERT 1966). Higher standing rises are swept by currents and, in places, covered with phosphate or manganese pavements (LONSDALE & LAWVER 1980; Fornari, pers. comm.).

Faults are a prominent feature of this region. Faults control basins and rises, but even on a smaller scale of tens of meters, the basin floor and slope is riddled with small, commonly normal faults. Observations from submersibles (LONSDALE & LAWVER 1980) reveal almost vertical scarps of soft Holocene diatomaceous turbidites. High resolution seismic profiling (e.g. MOORE 1973) also reveals numerous steeply dipping faults which conform to general transform orientations. Some normal faults, for example along the Conception Bay slope, show evidence of tilting and may resemble listric features, but these are secondary to the deep-seated vertical transcurrent faults. Grabens, or en echelon secondary faults are commonly oblique to the dominant strikes (MOORE 1973). Rifting fault movements have also isolated a string of islands, which were presumably connected to the mainland at one time. For example, the Isla Guardia and Isla San Esteban have been subjected to considerable tectonic jostling. Curiously, on the island of Tiburon, GASTIL & KRUMMENACHER (1977) have mapped a series of 20 imbricate, reverse faults of a young age, which cut the Oligocene and Miocene volcanics.

Outcropping volcanic flows are comparatively rare in the Gulf basins. One exception is the Isla Tortuga, a tholeiitic edifice, including considerable pillow lavas which occurs along the trace of the central transform fault in the Guaymas Basin (BATIZA 1978; LONSDALE & BATIZA 1980).

The area underlain by oceanic crust is presumedly confined to areas between major transform faults, but localized volcanic activity occurs where these faults project into landward areas. For example, near Santa Rosalia, large Quaternary, presumably alkalic volcanic cones rise along the trace of Transform V (Fig. 2). This region is also the site of extensive copper and manganese hydrothermal mineralization within porous Upper Pliocene sands (WILSON & ROCHA 1955). Clearly this mineralization occurs in conjunction with initial rifting events.

Pennine comparison

If we apply some features in terms of the Alpine Tethyan margin, it is of note that basinal subsidence in the Gulf of California, does not seem to be related to listric stretching of continental crust perpendicular to the margins but rather longitudinally along deep reaching vertical wrench fault segments. Pull-apart mechanisms rifting the continental blocks and depressions are subsequently backfilled by sediments and intrusions of basaltic magmas (CROWELL 1974).

The present features of the Gulf of California suggest that the bathymetry within the Pennine ocean was probably more complex than generally assumed. The Briançonnais Swell occurs as a 50–100 km wide "ribbon continent" asymmetrically tilted, with the gradual slope northwards. For example BOURBON et al. (1977) postulate numerous faulted slope basins along the apron in the Subbriançonnais Zone. Crinoidal limestone breccia, dolomite, rare coral debris and sands within some Bündnerschiefer units also suggest nearby local highs and fault blocks (KUPFERSCHMID 1977). PROBST (1980), for example, uses sediment source criteria to identify a Middle Jurassic Adula Swell to the southwest of the North Penninic realm (cf. BOLLI et al. 1980).

Troughs and rises which characterize the Mesozoic Alpine paleogeography formed in the Liassic, and some of the Austroalpine units are also thought to derive from small islands which persisted during Middle Jurassic to Middle Cretaceous (TRÜMPY 1975b). Steep vertical (normal?) faults are postulated to explain some breccias, and are cited as evidence of offshore banks, but may represent only modest extension (TRÜMPY 1975b). Fault block units are prominent along border regions between the Pennine and Austroalpine facies, but might suggest similar features basinward, if the movements were basically translational. Few of the tectonic elements suggest a Red Sea type of opening, thus TRÜMPY (1975b) hesitates to include orthogonal listric faulting as the only mechanism for crustal thinning.

DSDP results: sedimentation in the Gulf of California

The Gulf of California sediments are dominated by hemipelagic processes. In this arid region, seasonal rains turn low-relief, broad alluvial plains into torrential sheet flood zones. As the hinterland drainage areas are predominatly volcanic terrains, it is not surprising that fine-grained sands reaching basinal areas from perennial rivers along the eastern margin are mineralogically rather immature, with a high proportion of plagioclase. Most coarser grained sediment is trapped along the broad marginal shelves or in slope basins.

Deep Sea Drilling Project Leg 64 drilled 5 holes which dissected the Quaternary sedimentation patterns of the Guaymas Basin (CURRAY, MOORE et al. 1979; CURRAY, MOORE et al., in press). Bottom waters are poorly ventilated as a result of limited circulation and high organic productivity. Seasonal upwelling of nutrient-rich deeper water leads to massive diatom blooms. The pelagic diatomaceous component mixes with fine-grained terrigenous influxes along the hemipelagic slopes. Where these slopes intersect low-oxygen intermediate water masses, the deposits show typical varve-like couplets (CALVERT 1966). Radiolaria, foraminifera and nannofossils also flourish in this environment, but their numbers are overwhelmed by the dominantly diatomaceous and terrigenous signals.

Two holes (479 and 480) were located on the hemipelagic slopes, whereas three others (477, 478, 481) were located in the deep basin-plain or active rift trough areas of locally high heat flow. Basinal sedimentation rates are enormous, ranging from 400 to over 1200 m/m.y. which reflect the massive accumulation of turbidites, although the sediments are, for the most part, mixtures of fine-grained terrigenous muds and muddy diatomaceous oozes. These mud turbidites are difficult to recognize as such because classical turbiditic sedimentary structures are rare. Physical property measurements however reveal subtle grading (EINSELE & KELTS, in press). The contrast between turbidite and host is low because most of the basinal sediment has been redeposited from equivalent bathyal depths along the outer hemipelagic or delta slopes (EINSELE & KELTS, in press). Commonly, benthic foraminifera sieved from faintly graded beds are bathyal species, which have been displaced only short distances from their living environment (MATOBA & ODA, in press). Mass flows occur frequently in the localized troughs as a result of tectonic activity. The carbonate content of the hemipelagic sediments is low, ranging from 2 to 10%, or up to 25% in short intervals. Most carbonate derives from benthonic or planktonic foraminifera or nannofossils, although some layers are cemented by a diagenetically-formed dolomite (KELTS & MCKENZIE, in press). The sediments are indicative of reducing conditions, with 1-4% organic carbon, abundant pyrite and methane gas. Figure 3 compares the stratigraphy of one of the basinal sites with a Bündnerschiefer section.

DSDP results: ocean crust

Before drilling, a lack of clear magnetic anomalies, low bulk seismic velocities and diffuse, weak basement reflections had suggested that the oceanic crust in the Gulf of California was somehow different from that of well-defined spreading centers (CURRAY, MOORE et al. 1979). Pillow lavas were not encountered in any of the Leg 64 drill sites. Instead, the soft, unconsolidated, wet sediments are injected by irregular and complex multiple basaltic intrusions of tholeiitic composition, which affect the sediment in various ways (EINSELE et al. 1980). Sediment contact zones are common and include baked organics, newly-formed dolomite, chert, pyrite and carbonate cements. Sediments up to 40 m around sills show evidence of consolidation due to water expulsion. The texture of these doleritic sills is generally very coarse, but the sills themselves display only very thin (1-2 cm) chill margins (EINSELE et al. 1980). In Hole 481A, some thin sills show coarse-grained textures resembling gabbros with cm-size plagioclase and pyroxenes. Many sills show evidence of rapid alteration and display considerable porosity. An active hydrothermal regime was cored in 2000 m water at Site 477 to 260 m subbottom below a 30 m thick dolerite sill in the South Rift. The Holocene to Late Pleistocene diatom muds have been propylitized by a hydrothermal process similar to poaching in a steam cooker with the sill as a lid. The sediments beneath the sill show progressive metasomatic assemblages which change within 160 m from quartz-dolomite-anhydrite-illite, through a zeolite-K-feldspar, pyrite zone to a chlorite-epidote-quartz-albite-pyrrhotite assemblage. The paragenesis suggests temperatures reached 320 °C and over 180 °C was directly measured in the hole. The mineral paragenesis and temperature gradient point to a high temperature heat source, probably a recent intrusion, located just beyond the reach of the drill string. In thin section, minerals commonly show relict cores which indicate that the alteration of the young basinal

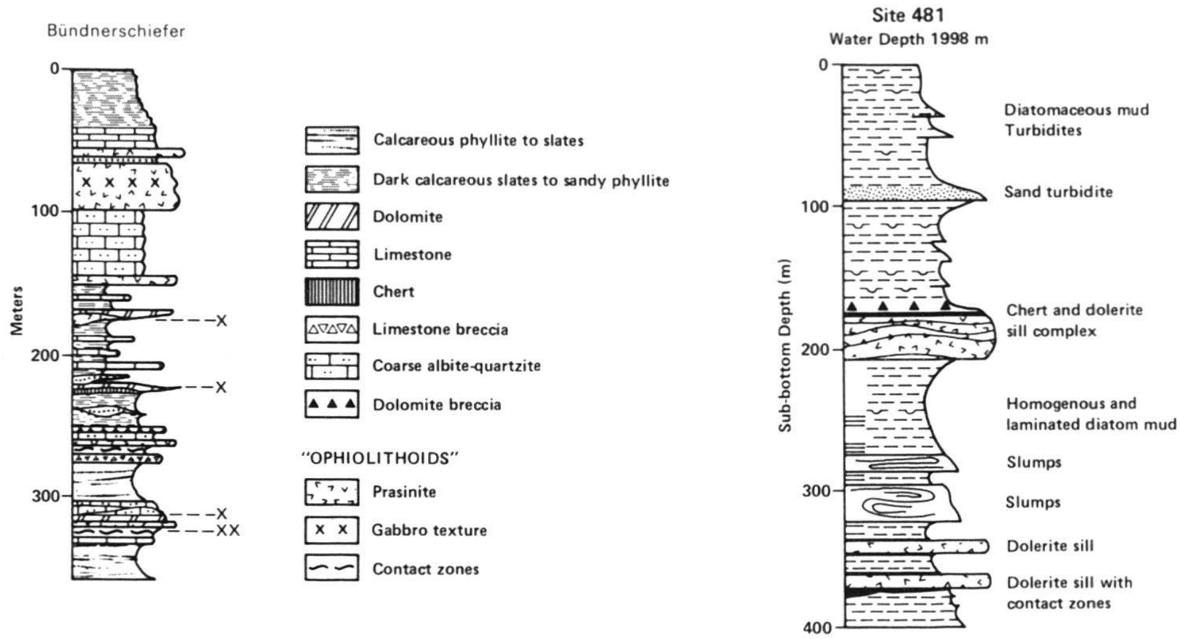

Fig. 3. Comparison of Late Pleistocene–Holocene stratigraphy of DSDP Site 481 in the North Rift of the Guaymas Basin, and a representative Middle Jurassic, metamorphic Bündnerschiefer section from the Northern Penninic Adula Trough which is projected from the geology of the northwestern ridge of the Bärenhorn in the Canton of Grisons (after Nabholz 1945). Imbricate thrust contacts are marked by (---×). The host sediment of both sections is fine-grained hemipelagic mud or mudstone (or slate) showing evidence of reducing conditions and redeposition. Thin complex sills show contact aureoles with chert and dolomite and coarse textures. Thin dolomite layers in the Guaymas Basin are also formed by early diagenetic processes. Sands in Hole 481 are plagioclase rich.

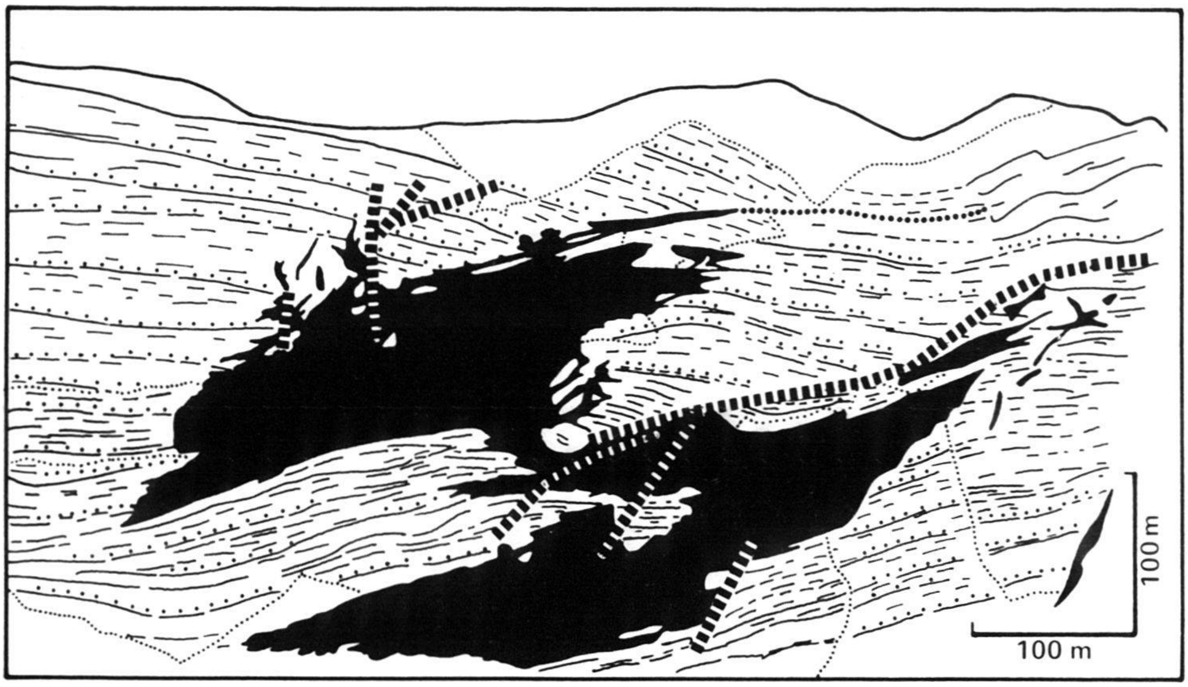

Fig. 4. Example of an outcropping doleritic sill body which intruded during lateral rifting phases into soft marine shale and turbidites of the lower Middle Miocene strata of the Lower Topanga Formation (after Crowell 1976) from an outcrop northeast of the Ridge Reservoir, Malibu, California. Illustrates irregular shape and enclosed sediment packages which are also presumed typical of igneous intrusions into the soft, wet Guaymas Basin muds.

sediments was rapid. The copper-rich district of Boleo, Santa Rosalia (WILSON 1955), is probably related to similar hydrothermal activity (Fig. 2). Single bit holes do not provide a view of the three-dimensional geometry of these basaltic intrusions, but seismic profiles and submersible observations in the rift troughs (LONSDALE & LAWVER 1980) suggest that they are localized features, generally with vaguely mushroom-like form. Basaltic magmas rise to some level of stress support in the soft, unconsolidated oozes, and then propogate horizontally, similar to laccolith mechanisms. Figure 4 illustrates an equivalent outcrop situation in Southern California where irregular basaltic intrusions occur in muddy turbidite sequences from an obliquely rifted setting (CROWELL 1976).

Implications

Few studies are available which specifically deal with Penninic sediments or tectonic units in terms of a translational margin in the Alpine Tethys. This section sketches some of the implications from a Gulf of California model which might influence some interpretations of field relations. Liassic rifting phases in the Tethys led to a complex paleogeography (TRÜMPY 1980; BERNOULLI & LEMOINE 1980), which included starved margins and basins, swells, slope basins, banks, shoals and troughs (BOURBON et al. 1977; PROBST 1980). These features can be the product of later wrench and transform movements in a broad belt, while crustal stretching occurs longitudinally. Interaction of irregular subparallel slices may squeeze some blocks downward by lateral pressure, whilst others subside by extension and concomitant basaltic injections (CROWELL 1974). The early stages of rifting morphology may resemble the present day California Borderland situation where subparallel strike-slip faulting regimes have formed a series of horst and grabens, defining numerous, moderately deep offshore basins on continental crust (MOORE 1969; JUNGER 1976). Tilting of large blocks of continental crust is observed in the Gulf of California, but does not seem to reflect major listric movements. Illustrative examples occur in the continental portion of Southern California. For example, within the San Jacinto system of fault slices, some basins only 4 km wide contain over 5 km of Late Tertiary sediment fill, or the narrow pull-apart Ridgebasin, with 7 km of Plio-Pleistocene sediment (CROWELL 1976). Vertical movements associated with similar broad wrench movements can form "Crystalline Ribbon Continents" stranded from mainland areas by small oceanic areas which are generated by pull-apart mechanisms.

Bündnerschiefer

The geology of the Middle Jurassic to Cenomanian (Northern Pennine) Bündnerschiefer formations in Eastern Switzerland remains poorly understood and the relationship to overlying flysch units is uncertain (Bolli et al. 1980). Recently, ISLER & PANTIĆ (1980) have interpreted "Schistes-lustrés" (Bündnerschiefer) series in terms of the oceanic phase of a general orogenic cycle. But great variability of rock types and local facies within this envelope terminology suggest that it is premature. KUPFERSCHMID (1977) and PROBST (1980) follow earlier authors and separate the Northern Pennine tectonic units into five general lithological types briefly summarized here:

1. Calcareous mica slates which alternate between more quartzose and more calcitic compositions. Some intercalated beds may contain echinoid or even coralline debris as well as rare radiolaria. Plagioclase grains are more common than K-feldspar. Pyrite and organic matter is ubiquitous and on fresh surfaces, these slates are dark bluish gray. A few coarser, sandy quartzose beds occur intercalated into some of the more northerly units.
2. Gray slates almost devoid of carbonate seem to derive from terrigenous sources sedimented into a modestly reducing environment.
3. Decimeter- to meter-scale massive limestone beds intercalated with some units are commonly recrystallized but contain plagioclase and quartz grains.
4. Some coarse-grained sandstones occur, cemented by calcite or quartz.
5. Some fine to coarse carbonate breccias and dolomitic layers occur in Middle Jurassic beds, commonly in proximity with "ophiolitoids" (prasinites; cf. TRÜMPY 1980).

There is some confusion on the criteria for depositional depth. Bündnerschiefer facies have been characterized as typically "deep-sea" or "deposited-below-the-CCD" implying bathyal to abyssial depths below about 4000 m (cf. ISLER and PANTIĆ 1980). Yet, the relative complex lithologies do not conform well with the notion of a normal oceanic realm. Earlier works for example (e.g. D. TRÜMPY 1916; JÄCKLI 1941; cf. NÄNNY 1948) tended to view the Bündnerschiefer as a trough sedimentation; laid down at modest depths, but generally deeper than the overlying flysch sandstones they considered, at that time, to be typical of shallow water sedimentation. Unfortunately, there is little conclusive information on the depth of depositional environment of Bündnerschiefer formations. The concept of calcium carbonate compensation depth (CCD) as a depth factor looses most of its meaning near continental margins (BERGER 1976). In areas of upwelling and high productivity, oxidation of abundant organic matter leads to a broad oxygen-minimum water mass that intersects the slope regions. In the Guaymas Basin this oxygen-minimum zone in the Gulf of California presently extends from around 600 m to 1400 m depth, but has apparently expanded in the past to include the whole basin.

If bottom conditions are completely anoxic, then dissolution characteristics are difficult to predict. In fact, alkalinity induced by sulfate reducers may lead to pristine calcite preservation (HÜLSEMANN & EMERY 1961). On the other hand, if even trace amounts of oxygen remain in bottom waters, the dissolution of calcareous nannoplankton and foraminifera is enhanced. This seems to have occurred in parts of the organic rich, but homogenous sections of the hemipelagic drape of the Guaymas Basin (MATOBA & ODA, in press). The amount of calcium carbonate will also be a function of the rate and composition of terrigenous supply. Calcium carbonate curves of the slope site DSDP Hole 480 for example are characteristically irregular with pulse-shaped variations from 2 to 25% (LE CLAIRE & KELTS, in press).

Slaty sequences of the Bündnerschiefer commonly comprise black, lustrous graphitic shales with significant pyrite; indicators of reducing conditions, at least within the sediment. Comparable organic carbon or calcium carbonate profiles are not available, but preliminary estimates suggest that Bündnerschiefer sediments were deposited more rapidly than most present deep-sea dissolution facies (HEATH et al. 1976).

Little precise information is available on sedimentation rates within Bündnerschiefer lithologies because of the poor dating control. BOLLI et al. (1980) have summarized the present stand for Northern Pennine regions and conclude that sedimentation was fairly continous from Upper Liassic sequences to Upper Cretaceous Flysch of Prättigau. These sediments overly a uniform Triassic facies deposited on presumably continental basement. The cumulative stratigraphic thickness of units in the Grisons is unknown but has been estimated at around 5 km (PANTIĆ & GANSSER 1977; TRÜMPY 1980). This would suggest an order of magnitude average accumulation rate of about 80 m/m.y. which is very close to those measured in the hemipelagic outer slope areas off the southern tip of Baja California (CURRAY, MOORE et al. 1979) and in other similar settings (LEGGET 1980). Because of the low relief carbonate platforms along contemporaneous Helvetic–Briançonnais margins, it is reasonable to expect times with lower accumulation rates in the Pennine Zone. No pyrolysis analysis have been published for dark shales of the Bündnerschiefer formations to determine whether the source of organics is terrestrial or marine (TISSOT & WELTE 1978). Palynological studies, however, show that both dinoflagellate and pollen populations are present (PANTIĆ & ISLER 1978). The relatively sparse pollen spectrum might suggest a region reasonably far from land, which is not unlikely considering the size of epicontinental seas at that time. Preservation of organic debris in the basins was then partly a function of oxygenation.

Another criterion quoted as evidence of a deep environment is the common presence of radiolaria which occur scattered in the sediment and as thin layers. These occurrences require further research but, as previously mentioned, radiolaria occur in the Gulf of California sediments up to shelf depths. WINTERER & JENKYNS (1979) and KOCHER (in press) have recently discussed possibilities that some radiolaria in the Tethyan Ocean occupied an ecological niche, similar to the present day diatoms, in nutrient rich upwelling areas and that some purer deposits were products of deposition on isolated offshore banks or marginal areas protected from terrigenous dilution. Certainly radiolarian-rich deposits were widespread in numerous environments during the Late Jurassic.

A lack of flysch-like sediment structures in Bündnerschiefer units has misled some to overlook redepositional processes. As noted, the Gulf of California Guaymas Basin contains turbidite facies, but because of the predominantly silty source areas, these mud turbidites are difficult to recognize. Commonly, beds have only a mm-thin sandy base and a massive, faintly graded body with a thin, commonly burrowed, lutite cap. Unfortunately, the metamorphic overprint in Bündnerschiefer units is just enough to confuse most such faint primary sedimentary structures and to discourage a search for these features, but there is also evidence that mud turbidites are common. Decimeter size, sandy-calcareous banks are intercalated; for example, in the monotonous Liassic–Dogger calc-schists of the Rosswald series

(BOLLI et al. 1980). In the Via Mala section (Cenomanian) fine-grained black to gray shales with mm-partings are interlayered with centimeter to decimeter homogenous calcareous beds which are surely redeposits. The Klus series of Prättigau (Cenomanian; BOLLI et al. 1980) also comprises slates and limestones interbedded on a decimeter scale. These show only faint metamorphic overprint and the surface weathering textures enhance structures which suggest that the limestone beds are lime turbidites. Detailed sedimentological studies are needed to clarify problems of redeposition. Problems of reconstructing source areas must also consider the possibility of conveyor-belt effects (CROWELL 1974) in translational regimes. If our interpretation is valid then, we may assume that by the time of Late Cretaceous compressional movements, source areas for Bündnerschiefer units may have been separated by hundreds of kilometers from their deposits.

Ocean crust

Brief mention is made of the similarities of mafic bodies in the Northern Pennine units and those drilled or surmised in the Guaymas Basin. For example, DIETRICH & OBERHÄNSLI (1975) ascribe thick metabasaltic (tholeiitic) layers associated with serpentinite and intercalated with Bündnerschiefer as the result of "local openings" of the Valais trough.

Complete crustal sections of the so-called ophiolite suite (cf. COLEMAN 1977) do not outcrop in the Penninic units of the Swiss Alps (DIETRICH 1976). The name ophiolite has been extended in the Alps to cover disjointed mafic rock packages which include masses of diabase; or larger slivers of meta-greenstones; pods of serpentinized peridotites; some pillow lavas, gabbro and diabase. Evidence of sheeted dikes is rare; pillow lavas are underrepresented, and layered cumulate ultramafics very rare (see DIETRICH et al. 1974).

In the Northern Pennine Zone most ophiolites comprise prasinite bodies (greenschist meta-basites), commonly interlayered concordantly on a scale of tens of meters to centimeter ribbonlets within the Bündnerschiefer phyllitic sediments (see Fig. 3; NABHOLZ 1945; LOUBAT 1968; KUPFERSCHMID 1977; PROBST 1980). They also include thin alternating bands of tholeiitic and sediment stringers or a variety of breccias with mafic to ultramafic components set in a carbonate cement which have been given special local names, such as "mixed-zones" or "ophistromatites" (NABHOLZ 1945).

LOUBAT (1968) arrived at a scenario similar to the DSDP results, after studying the mafic rocks of the Versoyen Zone along the Valais facies belt. These seem to grade into a transform boundary to the south, with an abrupt facies change to thick limestone breccias. The banded mafic intrusives seemed to suggest that magmas rose to a level of stress support in soft, wet sediments, and then injected laterally. He describes localized intense copper and manganese mineralization, similar to that caused by sill generated hydrothermal alteration of young sediments in the Guaymas area, and the more extensive deposits near the Baja margin (WILSON & ROCHA 1955). Even in more southerly Pennine units (e.g. Platta-Arosa Zone) where sedimentation rates are lower and pillow lavas common, DIETRICH (1969) has also described features which indicate the injection of basaltic intrusions into soft, wet sediments.

If compared with features of the Gulf of California model of oblique rifting, some characteristics of Alpine ophiolites (s.l.) make good sense. Transform fault zones are complex and several kilometers wide. Lherzolite pods, shielded by a serpentinite mantle might become tectonically emplaced in such regions. BONATTI et al. (1979) and others have discussed various occurrences of ultramafics in oceanic transform zones. Ophicalcite breccias are cited as partial evidence of such former transform faults in the Alps (e.g. DIETRICH 1976; LEMOINE 1980; DIETRICH & OBERHÄNSLI 1976).

The Guaymas Basin provides one explanation for the pre-orogenic setting of disjointed ophiolite members in the Valais Trough. The island of Tortuga stradles the short central transform segment of the Guaymas Basin. Isolated from the surrounding plain it is one of the few areas of pillow lava accumulation, and its lavas are tholeiitic with typical mid-ocean ridge geochemistry (BATIZA 1978). We have previously discussed the mushroom-like, erratically-shaped doleritic intrusions of all sizes (e.g. Fig. 4), which are injected into basinal muds. Thicker sills display very coarse gabbro-like textures. Serpentinite lenses along strike-slip zones may thus occur topographically higher in the basin than nearby pillow lavas. Therefore, it is important to note that in a translational regime most parts of an ophiolite suite may be locally and individually present at equivalent elevations in a basin rather than part of a cohesive vertical section of the crust.

Finally, in such regions where sediments and sills fill rifting margins, the concept "basement" becomes very difficult to define.

Oceanic metamorphism

Jumps in metamorphic grade and contact zones which occur in outcropping associations of Northern Penninic units fit well with the modern Guaymas Basin analogy. The DSDP Leg 64 drilling confirms that only a short span of a few thousand years is needed to produce a complete greenschist assemblage in rapidly deposited sediments near a rifting center. In the Guaymas Basin, modern heatflow is extremely variable, locally up to 30 HFU or as low as 2 HFU (LAWVER & WILLIAMS 1979) as the result of young intrusions. These intrusions expell considerable water from the sediments and, because of the shallow basin depth (2000 m), could be surrounded by a zone with steam generation. Short-lived, but intense hydrothermal systems developed (EINSELE et al. 1980). Equilibration of a metasomatic cell rapidly leads to zoned paragenesis including epidote-albite-quartz-chlorite in both older sills and sediment. The complex nature of such systems allows thermal events to persist locally at depth, while normal sediments accumulate above.

Near prasinite bodies in the Alps, zones of mineralization, silification, dolomitization and breccia are also encountered (NABHOLZ 1945; LOUBAT 1968; DIETRICH et al. 1974, Fig. 3). Typical albite-quartzites could, for example, derive from initially plagioclase-rich sand layers such as are common in the Guaymas Basin.

We can further predict that within the translational environments, buckling and jamming of tectonic slivers might cause basement thrusting concomitant with oblique spreading. Under enough cover, this might be accompanied by slightly higher pressure metamorphism.

Evolution of the Pennine realm: some speculations

The development of the Alpine system might follow from a combination of elements from the San Andreas strike-slip system, the California Borderlands and the Gulf of California. There has been up to 30 m.y. of lateral movement in this region, which retains mostly continental affinities (cf. CROUCH 1981). Figure 5 summarizes a hypothetical scheme for stages in the development of the Pennine Ocean from the Liassic to Late Cretaceous. It applies concepts of a translational margin rather than presenting a geometrically correct palinspastic reconstruction of the Alps.

Borderland phase: Liassic

The present California Borderland region is part of the San Andreas strike-slip system, now submerged. Up to several hundred kilometers of translation have been distributed over a broad region leading to a complex of basins and swells on continental crust (MOORE 1969; JUNGER 1976; CROWELL 1974). Sedimentation is variable; from hardgrounds to pelagic oozes to mass flows (NARDIN et al. 1979; JUNGER 1976; CROWELL 1976, 1974; CROUCH 1981) and most basins appear to be underlain by a continental type crust. Subsidence is a result, at least in part, of the dilitational movements along the strike-slip region.

Parallel with the opening of the North Atlantic (DEWEY et al. 1973) during the Liassic, the Eurasian-African Triassic platform may have been subjected to lateral shear stresses applied over a broad belt. The platform broke up into basins and swells of lozenge shaped blocks defined by the transcurrent movements which cut across facies belts (cf. BERNOULLI & LEMOINE 1980). Downdrop or tilted basins may have formed oblique to the margins, for example along the Subbriançonnais area.

Gulf of California phase: Middle Jurassic to Early Cretaceous

Shear patterns could have led to oblique rifting or pull-apart spreading along the trace of one or more of the strike-slip systems. This is followed by the relative stabilization of faulted slices along marginal areas because the lateral motion becomes more restricted to the central rift region. In this sense, there is a shift in some areas from translational to passive margin. Some pieces of the continental crust could become isolated by new oceanic crust, forming ribbon continents isolated from the mainland. Hemipelagic sedimentation of the Bündnerschiefer precursors continued, mostly along broad Northern Pennine slopes and partly in small basin plains. Serpentinite bodies or even gabbros could have been wedged up along fault traces, encased in ophicalcite breccias (e.g. DIETRICH & OBERHÄNSLI 1976). The morphology and facies changes in such a region may be quite variable. In a translational tectonic setting, spreading may turn on or off at geologically rapid rates, merely by a slight shift in the secondary vectors of motion. These changes can lead to synchronous extension or compression along the strike-slip pattern (e.g.

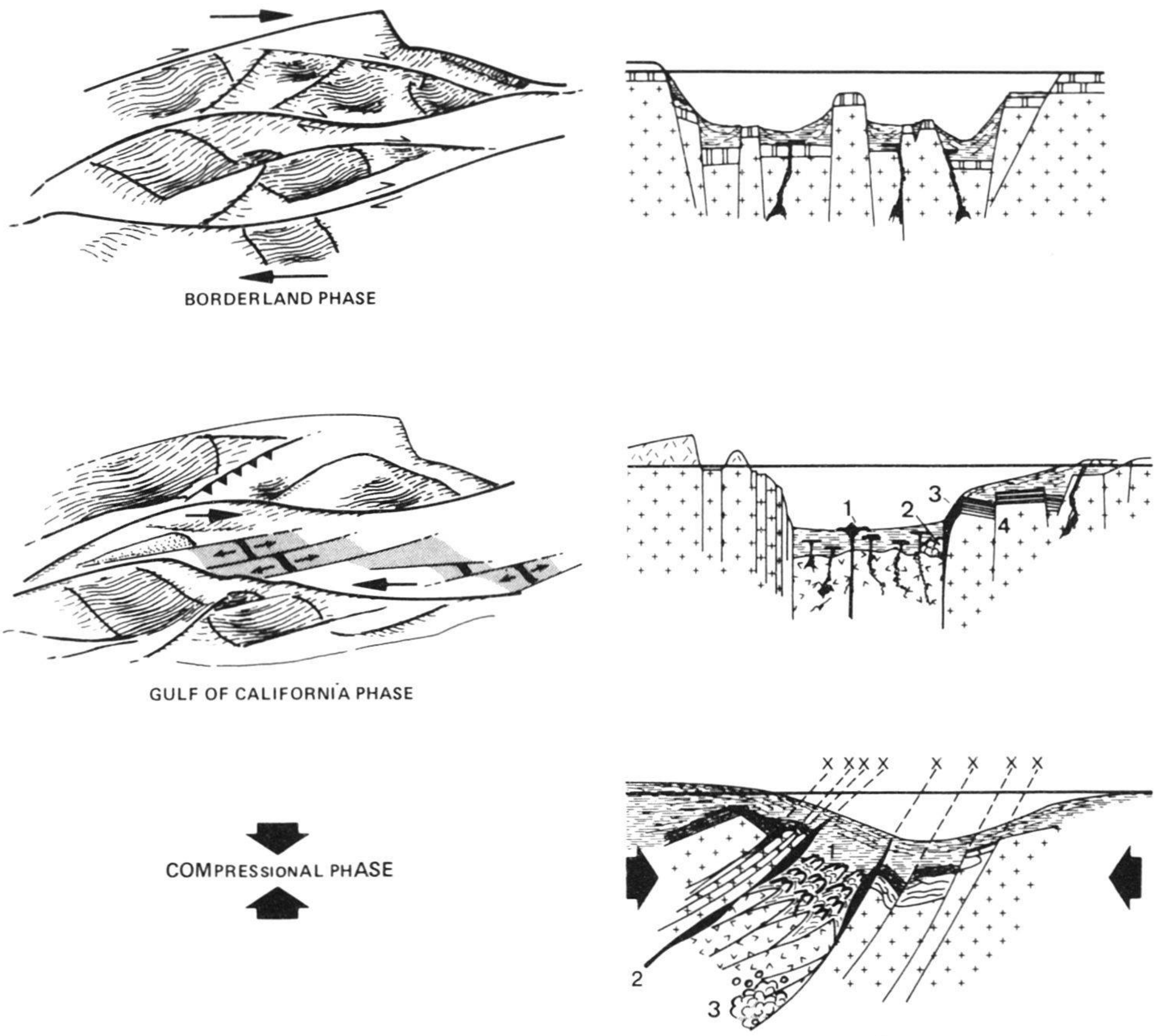

Fig. 5. Proposed process-model translational margin as a guide to the paleogeography of the Mesozoic Northern Penninic (Tethys) Ocean.

Borderland Phase based on the modern California Borderland region: Junger (1976), Crowell (1974), Crouch (1981). Translational stress applied over a large region leads to lozenge-shaped basin and ridge features with differential sedimentation. Some are isolated from terrigenous input. Facies include a large variety of pelagic, hemipelagic, and mass flows deposited on subsided continental crust, segmented by deep vertical faults. Volcanics in various positions.

Gulf of California Phase characterized by oblique rifting of continental blocks with spreading centers forming ocean crust, which may isolate some continental slivers. Marginal basins become more quiescent as lateral motion is accomodated along a restricted medial section. A narrow belt of irregular ocean crust forms in basinal areas with (1) sills injected into rapidly deposited soft hemipelagic oozes, (2) in some cases with concomitant hydrothermal alteration. (3) Ultramafic bodies may be tectonically emplaced along transform traces whilst (4) unconformities and changes in the hemipelagic slope facies are caused by differential dilational and compressional movements and tilting which affects continental blocks in the translational setting.

Compressional Phase: During initial compression, particularly if lateral motion continues, deep-seated transform or transcurrent faults may play a role in determining the zones of reverse and thrust fault shearing. Some possible concurrent events include: (1) deformation of interlayered sills and basinal sediment, (2) mobilization of ultramafic pods, (3) imbrication and shallow subduction of some oceanic crust (4) metamorphism at fairly shallow depths whereas normal hemipelagic sedimentation continues above.

CROWELL 1974), which may explain the somewhat restricted or staggered age of emplacement for outcropping mafic complexes. Obduction or basement thrusting may occur. Locally hydrothermal metamorphism occurs in association with relatively high heat flows and sill emplacement.

Compressional phase: Post Cenomanian

The Pennine Prättigau Flysch reflects changes to a compressional regime. More subaerial areas formed which shed coarser debris, from topographically more pronounced shelf areas. One explanation for thin crystalline thrust sheets in the Pennine Zone with a thin Mesozoic cover could be linked with tectonic blocks underlying slope areas and nature of the deep strike-slip faults. Possibly the deformation of these faults determined some initial slip surfaces for later nappes. The hemipelagic sediment within some outer slope basins might have then become enmeshed in advancing thrusts. TRÜMPY (1975b) has estimated that a few hundred kilometers might be taken up in crustal subduction by the imbricate stacking of the various tectonic units. If only a modest amount of oceanic crust and minor continental crust needed to be subducted, a fully developed Benioff Zone would be unnecessary. This could explain the lack of evidence for major arc volcanism and batholiths in the Alpine area. Further metamorphism and deformation of the Pennine units proceeds, including folding of the layered mafic intrusions in the Bündnerschiefer series. High pressure metamorphism can occur in conjunction with the imbrication of nappes. OXBURGH (1972), TRÜMPY (1975a) and HSÜ (1979) have discussed evidence and further implication of crustal subduction and thin-skinned tectonics in the Alps.

Conclusions: limitations and problems

The principles for oblique-slip regimes have been advanced by CROWELL (1974, 1976) and others. HOMEWOOD (1977) and CARON et al. (1979) previously applied these to Late Cretaceous Flysch of the North Pennine Valais Trough. This paper draws attention to the environment and recent Deep Sea Drilling findings in the Gulf of California as an actualistic process model for the general evolution of the Middle Jurassic to Middle Cretaceous Northern Pennine Basins. It can serve as a guide for unraveling the significance of fault zones, breccias and mafic intrusions in Bündnerschiefer particularly because the scale and complexity of the regions show many similarities. Differences in sedimentation must however be filtered.

One of the major limitations of this model is the difference in time span between 4 m.y. in the Gulf and perhaps 60 m.y. of translational motion through the Penninic Zone. Because an oblique opening of the Penninic region would be subject to constraints from the Eurasian-African Plates (BERNOULLI et al. 1979), we cannot predict the configuration that resulted from longer duration processes. The tholeiitic intrusions in the Valais Bündnerschiefer suggest that the formation of Gulf-of-California type crust occured during some periods, for instance, in the Dogger (PANTIĆ & ISLER 1978). A different configuration than the Gulf of California for transform faults and small spreading segments is necessary to isolate the Briançonnais sliver. Other tectonic slivers with continental affiliation such as the Tasna unit need reevaluation.

Northern Penninic Bündnerschiefer is interpreted as a hemipelagic deposit, probably including sedimentation in several slope basins. More field work is necessary; to locate possible source areas, possibly since removed by lateral movements; for unraveling the stratigraphic history and sediment transport mechanisms of Bündnerschiefer sequences with the help of palynology or radiolaria (PANTIĆ & ISLER 1979; BOLLI et al. 1980; KOCHER, in press); to better define the sedimentary characteristics, mineralogy, carbonate stratigraphy and organic geochemistry of Bündnerschiefer lithofacies. Also, the relation of Bündnerschiefer facies to Southern Piemont pelagic deposits remains unclear. The translational margin model implies that ophiolites, at least in the Swiss and Eastern Alps, are part of this regime. Possibly basinal swells or submarine ridges isolated more southerly regions from terrigenous dilution derived from not too distant northern sources as the Austro-Alpine and Southern Alpine units were part of a submerged continental margin (cf. BERNOULLI et al. 1979). Not enough is yet known about the paleoceanography of the E-W Tethys Ocean which was probably quite different than the modern Gulf of California. The symbiotic comparison of realistic modern and ancient analogs is however useful for progress in these complex areas.

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