Geology of the Hayward fault zone:
A digital map database

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Geologic Description

Introduction

The Hayward is one of three major fault zones of the San Andreas system that have produced large historic earthquakes in the San Francisco Bay Area (the others being the San Andreas and Calaveras). Severe earthquakes were generated by this fault zone in 1836 and in 1868, and several large earthquakes have been recorded since 1868. The Hayward fault zone is considered to be the most probable source of a major earthquake in the San Francisco Bay Area, as much as 28% chance for a magnitude 7 earthquake before the year 2021 (Working Group on California Earthquake Probabilities, 1990).

The Hayward fault zone, as described in this work, is a zone of highly deformed rocks, trending north 30 degrees west and ranging in width from about 2 to 10 kilometers. The historic earthquake generating activity has been concentrated in the western portion of the zone, but the zone as a whole reflects deformation derived from oblique right-lateral and compressive tectonic stress along a significant upper crustal discontinuity for the past 10 million or more years.

The Hayward fault zone is bounded on the east by a series of faults that demarcate the beginning of one or more structural blocks containing rocks and structures unrelated to the Hayward fault zone. The eastern bounding faults are, from the south, the Calaveras, Stonybrook, Palomares, Miller Creek, and Moraga faults. These faults are not considered to be part of the Hayward fault zone, although they are shown on the map to demarcate its boundary. The western boundary of the zone is less clearly defined, because the alluvium of the San Francisco Bay and Santa Clara Valley basins obscures bedrock and structural relationships. Although several of the westernmost faults in the zone clearly project under or through the alluvium, the western boundary of the fault is generally considered to be the westernmost mapped fault, which corresponds more or less with the margin of thick unconsolidated surficial deposits. The Hayward fault zone is truncated to the south by the Calaveras fault, which trends about north 10 west, and so forms an oblique east and south boundary. All of the faults within the southern part of the zone probably splay into the Calaveras fault. The northern margin of the zone as dealt with herein is San Pablo Bay, but the zone of deformation undoubtedly continues north of the Bay through the area bounded by the Rodgers Creek and Tolay faults.

Scientific study of the Hayward fault zone has had a long history. The first systematic study of the then called Haywards rift was undertaken soon after the major earthquake that occurred on the fault in 1868. However, this study was later lost or repressed by nervous local officials (Lawson, 1908). Following the 1906 San Francisco earthquake, the State Earthquake Investigation Commission, headed by A.C. Lawson, reinvestigated the 1868 earthquake. Their report (Lawson, 1908) contains a map of the Bay Area showing the approximate trace of the 1868 ground rupture. In 1914, Lawson published the San Francisco folio, in which he discussed the Hayward fault zone, although he did not show the Hayward fault on the accompanying maps because he could not locate the fault exactly. Since 1914, many workers have released larger scale geologic maps of areas including parts of the Hayward fault zone (Crittenden, 1951, Robinson, 1956, Hall, 1958, Radbruch and Case, 1967, Dibblee, 1972a-c, 1973a-b, 1980a-g, Radbruch, 1969, Graymer and others, 1994). In addition, topical studies on the Hayward fault zone have demonstrated its accumulated right-lateral and east-up offset (Russell, 1926, Buwalda, 1929), the formation of a groundwater barrier due to fault gouge (Forbes, 1949), and the evidence of fault creep at several points along the fault zone (Radbruch and Bonilla, eds, 1966). With the discovery of creep in the fault zone, and the prevailing model of future movement occurring where historic movement and present creep are known (Radbruch and Bonilla, 1966), several workers have produced different maps of the "active" strands within the fault zone based on creep, geomorphic, and trench studies (Radbruch-Hall, 1974, Herd, 1977, 1978, Helley and Herd, 1977, Lienkaemper, 1992). More recent work has focused on the relationship between the Hayward fault zone and the Calaveras fault (Andrews and others, 1993), the San Andreas fault (Zandt and Furlong, 1982), and the entire regional fault system (Jones and others, 1994).

Current thought regarding the Hayward fault seems to be that it is a relatively narrow, long lived zone of predominantly right-lateral strike-slip deformation (Lienkaemper, 1992). It is thought to connect to the Calaveras fault via a deep crossover structure in the region of Mission Peak (Andrews and others, 1993). The creeping strand is considered to be the locus of stress accumulation and probable future hazard (Radbruch and Bonilla, 1966).

Geologic relationships within the Hayward fault zone (as described below) indicate a much more complex geologic history for the fault, however. Recent observations (also discussed below) suggest late Holocene movement on strands within the zone other that the creeping strand (as most recently defined by Lienkaemper, 1992). In addition, there is evidence that a large amount of fault normal compression has also been taken up within the Hayward fault zone.

The purpose of this report is fivefold. 1) to demonstrate the short history of the creeping strand and to describe the structural history of the fault zone as a whole; 2) to illustrate potentially active strands within the Hayward fault zone in addition to the creeping strand defined by Lienkaemper; 3) to describe structures related to the Hayward fault zone including compressive structures; 4) to show possible Hayward - Calaveras fault connections in addition to that proposed by Andrews and others; 5) to describe rock types involved in the Hayward fault zone.

Description of rocks and map units in the Hayward fault zone

Overview

The rocks within the Hayward fault zone include sedimentary, igneous, and metamorphic rocks that range in age from Jurassic through Quaternary. The pre-Tertiary rocks are divided into two groups: the strongly to slightly metamorphosed igneous and sedimentary rocks of the Franciscan complex, and the relatively unmetamorphosed rocks of the Coast Range ophiolite and Great Valley sequence. The contact between these two pre-Tertiary groups is everywhere a fault. Throughout most of the mapped zone, the base of the Tertiary strata is also faulted, but Paleocene rocks are in unconformable contact with Great Valley sequence rocks in the Niles area, and middle Miocene rocks unconformably overlie Great Valley Sequence rocks in the Milpitas area.

Pre-Tertiary rocks are composed of two separate displaced terranes that were amalgamated during Late Cretaceous to early Tertiary time and subsequently underwent complex deformation, and were unconformably overlain by Tertiary strata. One of the terranes is the Franciscan complex, and the other is composed of the Coast Range ophiolite and Great Valley sequence. Both terranes contain bedded rocks as young as Late Cretaceous (Campanian), so amalgamation must post-date Campanian deposition.

Following is a description of the rocks and map units contained in the Hayward fault zone. For more complete descriptions of some of the units see Graymer and others (1994), Hall (1958), Radbruch (1969), Crittenden (1951), Graymer (1995), Bailey and others (1964), and Savage (1951)

Franciscan Complex

JKfm — Franciscan melange (Late Jurassic and Early Cretaceous). Sheared black argillite, graywacke, and meta-graywacke containing blocks and slabs of meta-graywacke and shale (fs), chert and metachert (fc), serpentinite (sp), greenstone (gs), amphibolite, tuff, eclogite, quartz schist, greenschist, basalt, marble, conglomerate, and blueschist. Blocks range in size from a few millimeters to several hundred meters in length. Only some of the largest blocks and slabs are shown on the map.

JKfn — Sandstone of Novato Quarry (Late Cretaceous). Distinctly bedded to massive, fine- to coarse- grained, mica bearing, lithic wacke. Where distinctly bedded, sandstone beds are about one meter thick, and siltstone interbeds are a few centimeters thick. Sedimentary structures are well preserved. In the type area in Marin County, about 20 km northwest of the map area, fossils of Campanian age have been discovered (Bailey and others, 1964). In north Oakland, the sandstone is associated with a large body of fine-grained quartz diorite (JKfgm). Although the margins of the intrusive body are pervasively sheared, the magma was probably originally intruded into the sandstone. This relationship is demonstrated by hydrothermal alteration that has changed the non-quartz grains in the sandstone into white powder, probably clay minerals, in many parts of the sandstone outcrop area.

JKf — Undivided rocks of the Franciscan Complex (Late Jurassic to Late Cretaceous).

Coast Range Ophiolite and Great Valley Sequence

Coast Range Ophiolite (Jurassic). Consists of:

sp — Serpentinite. Mainly sheared serpentinite, but also includes massive serpentinized harzburgite.
Jgb — Gabbro
Jb — Massive basalt and diabase.
Jpb — Pillow basalt, basalt breccia, and minor diabase.

Overlying Volcanics

Jsv — Keratophyre and quartz keratophyre (Late Jurassic). Highly altered intermediate and silicic volcanic and hypabyssal rocks. Feldspars are almost all replaced by albite. In some places, closely associated with (intruded into?) basalt. This unit includes rocks previously mapped as Leona and Northbrae rhyolite, erroneously considered to be Tertiary (Dibblee, 1980, 1981, Radbruch and Case, 1967, Robinson, 1956). Recent biostratigraphic and isotopic analyses have revealed the Jurassic age of these rocks (Jones and Curtis, 1991). These rocks are probably the altered remnants of a volcanic arc deposited on ophiolite during the Jurassic.

Great Valley Sequence (Late Jurassic to Late Cretaceous). Consists of:

JKk — Knoxville Formation (Late Jurassic and Early Cretaceous). Mainly dark, greenish-gray silt or clay shale with thin sandstone interbeds. Locally includes thick pebble to cobble conglomerate beds in its lower part (JKkc). Locally at the base includes beds of angular, volcanoclastic breccia (JKkv) derived from underlying ophiolite and silicic volcanic rocks. The depositional contact of Knoxville formation on ophiolite and silicic volcanic rocks is preserved in several locations in the Hayward fault zone.

Knc — Sandstone and shale of Niles Canyon (Early Cretaceous, Albian). Distinctly bedded, gray to white, well lithified, massive to cross-bedded, biotite-bearing, coarse- to fine-grained sandstone, siltstone, and shale. Sandstone varies from biotite and quartz rich wacke to lithic wacke. Plant debris is common. Sandstone tends to form discontinuous outcrops on the ridges and uplands and prominent resistant outcrops in canyons, whereas siltstone and shale are largely visible only in canyons. This formation is equivalent to part of the Niles Canyon formation of Hall (1958)

Kjm — Joaquin Miller Formation (Late Cretaceous, Cenomanian). Thinly bedded shale with minor sandstone. Grades into thinly bedded, fine-grained sandstone near the top of the formation. The contact with the overlying Oakland Sandstone is gradational.

Ko — Oakland Sandstone (Late Cretaceous, Cenomanian and/or Turonian). Massive, medium- to coarse-grained, biotite and quartz rich wacke. Contains prominent interbedded lenses of pebble to cobble conglomerate. Conglomerate clasts are distinguished by a large amount of silicic volcanic detritus, including quartz porphyry rhyolite. Conglomerate composes as much as fifty percent of the unit in the Oakland hills, but it becomes a progressively smaller portion of the unit to the south.

Kcv — Unnamed sandstone, conglomerate, and shale of the Castro Valley area (Late Cretaceous, Turonian and younger(?)). The lower part of the unit is composed of distinctly bedded, mica bearing siltstone, fine-grained mica bearing wacke, shale, and, locally, one thin pebble conglomerate layer. The middle part of the unit is composed of distinct, thick beds of medium- to coarse-grained, mica rich wacke and pebble to cobble conglomerate. The middle part grades upward into distinctly to indistinctly bedded, medium- to fine-grained, mica rich wacke and siltstone. This unit is bounded above and below by faults.

Ksc — Shephard Creek Formation (Late Cretaceous, Campanian). Distinctly bedded mudstone and shale, mica rich siltstone, and thin beds of fine-grained, mica rich wacke. This formation is conformably overlain by the Redwood Canyon Formation.

Kr — Redwood Canyon Formation (Late Cretaceous, Campanian). Distinctly bedded, cross-bedded to massive, thick beds of fine- to coarse grained, biotite and quartz rich wacke and thin interbeds of mica rich siltstone. This formation is conformably overlain by the Pinehurst Shale.

Kp — Pinehurst Shale (Late Cretaceous, Campanian). Siliceous shale with interbedded sandstone and siltstone. Includes maroon, concretionary shale at base. This formation was originally considered to be Paleocene, but it contains foraminifers and radiolarians of Campanian age in its type area and throughout its outcrop extent.

Ku — Undivided, unnamed sandstone and siltstone (Cretaceous)

Kc — Undivided, unnamed conglomerate (Cretaceous)

Tertiary strata

Tas — Unnamed glauconitic sandstone (Paleocene). Coarse-grained, green, glauconite rich, lithic sandstone with well preserved coral fossils. Locally interbedded with gray mudstone and hard, fine-grained, mica bearing quartz sandstone. Outcrop of this unit is restricted to a small, fault bounded area in the Oakland hills.

Tps — Unnamed siltstone and sandstone (Paleocene). Dark gray, indistinctly to distinctly bedded siltstone, claystone, and shale. Grades downward into a basal, indistinctly bedded, dark brown to green, coarse-grained, glauconite bearing, lithic sandstone. This unit rests unconformably on unnamed Late Cretaceous sandstone and shale east of Niles. It is about 100 meters thick. Overlying strata have been faulted or eroded away. Three samples of the mudstone have yielded abundant coccolith floras of late Paleocene (CP-8) age (D. Bukry, U.S. Geol. Survey, written comm., 1992).

Tes — Unnamed mudstone (Eocene). Green and maroon, foraminifer rich mudstone, locally interbedded with hard, distinctly bedded, mica bearing, quartz sandstone. This unit is bounded above and below by faults.

Tolman Formation of Hall (1958) (Eocene?). Divided into:

Ttls — Gray, algal limestone, interbedded with white, calcium carbonate matrix pebble conglomerate, and clean, medium- to coarse-grained sandstone with calcite cement. Sandstone grains include quartz, feldspar, and lithic fragments, and in places include a large percentage of algal debris. Sandstone weathers to orange color.

Tts Dark gray to dark greenish-gray, indistinctly bedded, glauconite bearing, medium- to coarse-grained lithic sandstone. Locally interbedded with minor amounts of fine-grained sandstone and siltstone.

The Tolman Formation is bounded above by a fault. It overlies Redwood Creek Formation sandstone and Pinehurst shale along an obscured contact.

Tgs Unnamed glauconitic mudstone (Oligocene(?) and Miocene). Brown mudstone, interbedded with glauconite grain sandy mudstone. Locally mudstone and sandy mudstone contains phosphate nodules up to one centimeter in diameter. Locally interbedded with brown siltstone and fine-grained sandstone (Tgss). This unit is bounded below and above by faults. This unit is equivalent to the Sobrante(?) Formation of Radbruch (1969).

Tsh Unnamed sandstone, shale, chert, and dolomite (early Miocene). Sandstone is massive, medium-grained quartz arenite which weathers orange. The sandstone is interbedded with dark gray siltstone and claystone containing many concretions, and some conglomerate. The conglomerate contains pebbles of varicolored chert, andesite, and quartzite in dolomite matrix. This formation also includes a breccia at the base containing large (1-2 meters long) angular to subrounded blocks of dolomite, chert, siliceous shale, and sandstone containing plant fragments, in a highly sheared siltstone and argillite matrix. A concretion in the shale has yielded Siphogenerina transversa and a rich benthic fauna of late Saucesian (early Miocene) age (K. McDougall, U.S. Geol. Survey, written comm., 1992). This unit is limited to a small, fault bounded lens near the mouth of Niles Canyon.

Ts Sobrante Sandstone (middle Miocene). White, fine- to medium-grained quartz sandstone. Occurs in discontinuous outcrops below the base of the Claremont Formation, in fault contact with underlying Cretaceous strata.

Claremont Formation (middle to late Miocene). Divided informally into:

Tcc Chert and siliceous shale member. Chert occurs as distinct, massive to laminated, gray or brown beds as much as 10 cm thick with thin shale partings. Distinctive black, laminated chert occurs in Alum Rock Canyon and in minor amounts in the Mission Pass area and the Berkeley Hills. Siliceous shale is dark brown to gray, finely laminated, with grains as large as silt size. Some of the shale contains abundant foraminifers and fish scales. This member also contains prominent interbedded lenses of massive, tan, foraminifer-bearing dolomite as much as one meter in length, that weathers to a distinctive yellowish orange color. The Claremont chert and shale member is similar to the Tice Shale, but is distinguished by the presence of chert and more siliceous shale.

Tcs Sandstone and siltstone member. Light brown, gray, and white, fine-grained quartz sandstone and siltstone.

The Claremont formation is fault bounded above and below throughout the Berkeley and Oakland hills. It unconformably overlies the Sobrante Sandstone in the Niles area, and unconformably overlies Cretaceous strata in the Milpitas area.

To Oursan Sandstone (middle to late Miocene). Brown to tan siltstone and fine-grained sandstone, and distinctly to indistinctly bedded black mudstone. In places the sandstone contains large amounts of secondary calcite. The sandstone locally contains large lenses, as long as 2 meters, of tan, foraminifer bearing dolomite that weather to a distinctive yellowish orange color, similar to those found in the Claremont Formation. Poorly preserved foraminifers are common in the siltstone and mudstone beds. This unit only occurs in the Mission Pass area, where it lies conformably on the Claremont Formation.

Tt Tice Shale (late Miocene). Distinctly bedded, dark brown, gray, and tan, siltstone, mudstone, and siliceous shale. Tice Shale weathers locally to a reddish brown color. The shale contains numerous lenses of massive, tan dolomite, as much as two meters in length, that weather to a characteristic yellowish orange color, similar to those found in the Oursan and Claremont Formations. Locally, the shale also contains abundant fish scales. This unit only occurs in the Mission Pass area, where it lies conformably on the Oursan Sandstone.

Tbr Briones Formation (late Miocene). The basal part of this Formation consists of distinctly bedded, gray to white, fine-grained sandstone and siltstone. Sandstone beds are as thin as 5 to 10 cm, with 2 to 10 cm thick shale interbeds. These are interbedded with massive fine-grained sandstone beds as much as five meters thick. The middle part of the Formation consists of indistinctly bedded, white, fine- to coarse-grained sandstone, conglomeratic sandstone, and massive shell-hash conglomerate (shell beds). Shell-hash conglomerate is made up of interlocking mollusk and barnacle shells and shell fragments in a white calcareous sandstone matrix. The upper portion of the Formation consists of distinctly to indistinctly bedded, massive to cross-bedded, fine- to coarse-grained white sandstone. The Briones Formation is restricted to the southern part of the Hayward fault zone. It lies for the most part unconformably over the Claremont Formation, but lies conformably on the Tice Shale where that unit is present.

Tor Orinda Formation (late Miocene). Distinctly to indistinctly bedded, non-marine, pebble to boulder conglomerate, conglomeratic sandstone, and coarse- to medium-grained lithic sandstone. Clasts are sub-angular to well rounded, and contain a high percentage of detritus derived from the Franciscan complex. The Formation locally includes interlayered bright green porphyritic dacite sills (Torv) with phenocrysts of quartz and plagioclase and large xenoliths of pink and red chert. Orinda Formation lies unconformably over Briones Formation in the southern part of the Hayward fault zone, but is faulted at the base in the northern part.

Tm Moraga Formation (late Miocene). Basalt and andesite flows, with minor rhyolite tuff. Ar/Ar ages ranging from 9.0+-0.3 to 10.2+-0.5 Ma have been reported from the Moraga Formation (Curtis, 1989). Interflow sedimentary rocks (Tms) are mapped locally. The Moraga Formation conformably overlies the Orinda Formation in the northern part of the Hayward fault zone.

Tst Siesta Formation (late Miocene). Non-marine siltstone, claystone, sandstone, and minor conglomerate. The Siesta Formation conformably overlies the Moraga formation.

Tbp Bald Peak Basalt (late Miocene). Massive basalt flows. Ar/Ar ages ranging from 8.37+-0.2 to 8.46+-0.2 Ma have been reported from this unit (Curtis, 1989). Bald Peak Basalt conformably overlies the Siesta Formation.

Tn Neroly Sandstone (late Miocene). Blue or white, volcanic-rich, shallow marine sandstone. This unit only occurs within the Hayward fault zone as a small fault lens east of Oakland.

Tv Unnamed volcanic rocks (late Miocene or early Pliocene). This unit shows remarkable variation in lithology, although it occurs in only a small area northwest of Niles. In the southern part of the outcrop area it consists of white to gray, rhyolite to andesite, interbedded pyroclastic flows, tuff, volcanic breccia, and volcanoclastic conglomerate. In the northern part, the rocks are mainly black or red porphyritic basalt. Phenocrysts include plagioclase, pyroxene, and olivine. The volcanic rocks unconformably overlie the Orinda formation.

Tss Unnamed sandstone and conglomerate (Tertiary). Red, coarse-grained, glauconite bearing lithic sandstone and pebble conglomerate. Contains many small pectin and other invertebrate fossils locally. Occurs within the Hayward fault zone only as two small fault lenses east of Berkeley.

Pliocene and Pleistocene Gravels

Tsk Silver Creek Gravels of Graymer and DeVito (1993) (Pliocene). Interbedded conglomerate, sandstone, siltstone, tuffaceous sediments, tuff and basalt. This unit is distinguished from other gravels by the presence of interbedded volcanic rocks, the interbeds of nonmarine green and red mudstone, its relatively well consolidated nature, and by clast composition. About 75% of the detritus is derived from Franciscan rocks, whereas the other 25% is derived from volcanic rocks, chert from the Claremont Formation, and other Cenozoic rocks. An interbedded basalt within this unit has been dated at 2.6 Ma (Nakata and others, 1993), and a interbedded tuff within Silver Creek Valley has been dated at about 3 to 4 Ma (M. Wills, Cal. State. Univ. San Jose, personal comm., 1995). The base of this unit is nowhere exposed, and the top is cut by the Silver Creek thrust.

QTp Packwood Gravels of Crittenden (1951) (Pliocene and Pleistocene(?))**.** This rock unit generally consists of gravel to cobble (rare) silty and fine sandy conglomerate, fine silty sandstone, gravely to fine sandy siltstone, and minor olive-green claystone beds. Noteworthy is the presence of numerous nonmarine red beds in the unit. This unit differs from all other gravels in that the clasts are composed almost entirely of detritus derived from conglomerates and sandstone of the Cretaceous Great Valley Sequence. The base of this unit is interbedded with and coeval to the Silver Creek gravels (M. Wills and D. Andersen, Cal. State Univ. San Jose, personal comm., 1995). However, the top of the unit postdates and overlaps the Silver Creek thrust, which postdates the deposition of the Silver Creek Gravels

QTl Livermore Gravels (Pliocene and/or Pleistocene). Poorly to moderately consolidated, indistinctly bedded, cobble conglomerate, gray conglomeratic sandstone, and gray coarse-grained sandstone. Also includes some siltstone and claystone. Clasts contain mostly graywacke, chert, and metamorphic detritus probably derived from the Franciscan complex. There are no known age diagnostic fossils or volcanic rocks from the Livermore Gravels within the Hayward fault zone. The unit is, however, very similar, and may be equivalent to, the Irvington Gravels.

QTi Irvington Gravels of Savage (1951) (Pliocene(?) and Pleistocene). Poorly to well consolidated, distinctly bedded cobble conglomerate, gray conglomeratic sandstone, and gray, coarse-grained, cross-bedded sandstone. Clasts consist of about one-half micaceous sandstone derived from both the Great Valley Sequence and the Franciscan complex, and one-half chert, metamorphic and volcanic rocks derived from the Franciscan complex.. The gravels also include rare but distinctive clasts of laminated black chert from the Claremont Formation. A large number of Pleistocene (Irvingtonian) vertebrate fossils has been collected from this unit (Savage, 1951). The fossils are restricted to a relatively narrow horizon, however, so it is possible that this unit could contain strata as old as Pliocene.

Quaternary Deposits

Qoa Unnamed gravels and terrace deposits (Pleistocene). Poorly to moderately consolidated, boulder to pebble conglomerate and coarse-grained lithic sandstone. Clasts composition varies greatly. Late Pleistocene (Rancholabrean) age fossils have been reported from two localities in this unit (UCV 5928 and UCV 6304 in Hayward quadrangle, UCV 5834 in Oakland East quadrangle).

Qls Landslide deposits (Pleistocene and/or Holocene). Poorly sorted clay, silt, sand, and gravel. Only a few very large landslides have been mapped. For a more complete map of landslide deposits, see Nilsen and others (1979).

Qu Undivided surficial deposits (Pleistocene or Holocene). Includes alluvial fan, levee, stream channel, bay mud, floodplain, and floodbasin deposits.

Qm Manmade deposits (Holocene). Landfill and dams.

Structures within the Hayward fault zone

Overview

The Hayward fault zone, as described in this paper, is a broad zone of deformation 2 km to 10 km wide, trending approximately north 30 west from an area east of San Jose to San Pablo Bay (and perhaps beyond). The zone is bounded on the east by a series of faults that are the result of deformation not related to the Hayward fault zone, including the Calaveras, Stonybrook, Palomares, Miller Creek, and Moraga faults. These are shown as Eastern boundary faults on sheet 3. The western boundary of the fault zone is not as well defined because it is obscured by Quaternary deposits of the San Francisco Bay basin. Several mapped faults must cut or extend beneath these deposits, but not enough data are available to portray the location of these faults accurately. Therefore the western margin of the Hayward fault zone is provisionally regarded as the westernmost fault trace shown on our map, which corresponds more or less with the onlap of thick Quaternary deposits.

Within the zone, structures reflect compressional, extensional, and right-lateral strike-slip deformation. The zone can be arbitrarily divided into four subzones, areas within which the dominant structural style is relatively uniform. The segregation of structural style into these areas is a result of changing location and style of deformation during the development of the Hayward fault zone through geologic history.

Structural Subzones

The four structural subzones are named for their relative geographic position within the Hayward fault zone: San Pablo, San Leandro, Castro Valley, and Fremont. Each contains a distinct structural style.

The San Pablo subzone is dominated by east vergent reverse faults. In this subzone, bedrock is close to the surface throughout and west of the fault zone, as opposed to the San Leandro subzone and most of the Fremont subzone where depth to bedrock increases rapidly west of the alluvial boundary. The youngest rocks offset by the structures in this subzone are late Miocene volcanic rocks. The Wildcat fault, however, has geomorphic features that indicate Quaternary offset.

The San Leandro subzone is bounded by the Chabot fault and the alluvial flat of the Bay. It is characterized by the presence of the oldest rocks in the fault zone (Franciscan, ophiolite, keratophyre, and Knoxville), and closely spaced, imbricate, west vergent thrust and reverse faults. Several of the faults in this subzone cut late Pleistocene (Rancholabrean) or younger alluvial deposits. Many of the faults are confined to the Jurassic and Cretaceous rocks, however, and probably are related to Campanian or younger amalgamation of Franciscan and Coast Range Ophiolite/Great Valley sequence rocks. The Pleistocene or younger faults may be reactivated strands of the older fault system.

The Castro Valley subzone lies east of the Chabot fault. It is bounded on the south by the Sheridan Creek fault. The structures in the Castro Valley subzone may be related in part to those in the San Pablo subzone. They are broadly spaced, east-vergent reverse and thrust faults. One fault is synformal, creating a detached plate of Late Cretaceous strata (Graymer, Jones, and Brabb, 1995b). The youngest rocks cut by these faults are middle to late Miocene (Claremont Formation), and there is no evidence of Quaternary deformation in the Castro Valley subzone.

The Fremont subzone includes and lies south of the Sheridan Creek fault. A fault within this subzone, the Mission fault, truncates and offsets the Chabot fault in the vicinity of Niles, where the Chabot fault forms the boundary between Knoxville formation on the west and Miocene strata on the east. The Mission fault cuts and offsets this boundary approximately 7.5 km in a right lateral sense. These offset points are labled A and B on sheet 2 (hfsplt.ps). This subzone contains broadly to moderately closely spaced, west-vergent reverse and thrust faults. Faults in this subzone cut Pleistocene (Irvingtonian) gravels. In addition, the offset of the Chabot fault by the Mission fault indicates late Pleistocene or younger offset on the Mission fault. Active seismicity has been recorded on several faults within this subzone.

The Hayward fault zone connects to the Calaveras fault zone via the faults in the Fremont subzone. Andrews and others (1993) emphasized the trend of deep seismic activity in the Mission Peak region as the connecting link. However, active seismicity also occurs along faults in the Fremont subzone south of Mission Peak, such as the Warm Springs fault (Walter and others, in press). In addition, the 1868 Hayward fault rupture extended as far south as Milpitas, about 16 kilometers south of the proposed connection (Lawson, 1908). Average creep rate along the creeping strand south of the proposed connection (8 mm/yr.) is higher than the average rate north of the connection (6 mm/yr., Lienkaemper, 1992). And finally, there is geomorphic evidence for late Quaternary offset on the Clayton fault in the area east of San Jose (Dibblee, 1972c). These data suggest that rather than a single connection, the Hayward fault zone connection to the Calaveras fault zone is distributed through many of the faults in the Fremont subzone, of which the Mission crossover is only one example.

The amount of right-lateral offset of late Miocene or older rocks along the Hayward fault zone remains controversial. Estimates range from 7 to 27 km based on identification of possible source terranes for the Orinda Formation (Graham and others, 1984), to as much as 190 km, based on matching the Tolay volcanics north of the map area in Sonoma County with the Quien Sabe volcanics south of the map area in Santa Clara County (although an undetermined amount of that 190 km is also apportioned to the Calaveras fault zone, Jones and Curtis, 1991). Linieki-Laporte and Andersen (1988) estimated 38 km of latest Miocene (late Hemphilian or about 7.7 to 6.5 Ma) Hayward fault offset based on matching the lower part of the Mulholland Formation east of the Hayward fault zone in Contra Costa County with the Petaluma Formation north of the study area in Sonoma County. The Mulholland is not cut by the Hayward fault zone, however, but by the Moraga-Miller Creek faults, so the 38 km can only be considered an estimate of post-late Miocene offset on those faults. An intermediate estimate of post-late Miocene offset on the Hayward fault zone is 43 km based on matching the Tolay volcanics with the Moraga volcanics (Fox and others, 1985, Curtis, 1989, Jones and Curtis, 1991) because of the presence of coeval (about 8 Ma) titanaugite bearing basalt flows in each. Strong lithic contrast between the units as a whole casts doubt on the correlation, however (Jones and Curtis, 1991). In addition, the pre-Moraga and pre-Tolay units do not match, requiring pre-late Miocene offset along the fault zone. The evidence of 30 km or more of post-late Pliocene right-lateral offset within this study area (see below) is inconsistent with the small amounts of offset (7-27 km) proposed by Graham and others (1984). The evidence is consistent with the intermediate estimate of 43 km, but suggests an acceleration of offset in the last 2 Ma from a long term rate of 13 km/ 6 Ma to 30 km/ 2 Ma. Given the uncertainty of the correlation of the Tolay and Moraga volcanics, we provisionally accept the estimate of 43 km post-late Miocene offset as a minimum figure. It is important to note that very little of this offset has occurred on the creeping strand. Based on offset Jurassic and Cretaceous units between Niles and Berkeley, as little as 3 km of offset has occurred along the creeping strand. An example of this small amount of offset is indicated by the apparent 3 km displacement of a body of keratophyre cut by the creeping strand in east Oakland. This offset is denoted by points C and D on sheet 1 (hfnplt.ps).

Structural History

The oldest structures within the Hayward fault zone involve the Jurassic and Early Cretaceous rocks in the San Leandro subzone. The rocks are imbricated by closely spaced thrust faults. Some of the interleaving is probably related to initial amalgamation of Franciscan complex and Coast Range ophiolite/Great Valley sequence terranes. As shown by the presence of Campanian strata in both terranes, amalgamation occurred after Campanian deposition in the latest Cretaceous or early Tertiary. This juxtaposition must have been largely completed by Miocene time because the same Miocene rocks (including Claremont and Sobrante Formations) were deposited on both terranes. The depositional contact of Miocene rocks on Franciscan rocks is not preserved within the Hayward fault zone, but is just east of the zone in the area of Sunol Regional Park.

During the late Miocene to early Pliocene, deformation was dominated by broadly spaced, east-vergent thrust faults. These structures are preserved in the San Pablo and Castro Valley subzones. Although many of the structures in the Castro Valley subzone cut predominantly Late Cretaceous rocks, fault slices of middle to late Miocene rocks in the vicinity of Upper San Leandro Reservoir demonstrate that these structures are late Miocene or younger. Even though the faults at this time were more widely spaced than earlier faults, the amount of compressive deformation remains very large. One unnamed, synformal, folded thrust fault in the Castro Valley subzone doubles the Cretaceous section by stacking Joaquin Miller Formation and Oakland Sandstone on top of Shephard Creek and Redwood Canyon Formations and Pinehurst Shale (Graymer, Jones, and Brabb, 1995b). Large scale right-lateral offset was also occurring in late Miocene to early Pliocene time. As discussed above, late Miocene rocks have been offset at least 43 km. At least 13 km of offset probably took place during late Miocene and early Pliocene time.

During the late Pliocene to early Pleistocene, deformation seems to have been concentrated along the Chabot fault. The Chabot fault underwent 23 km of right lateral offset, based on correlation of Pleistocene gravels (Graymer, Jones, and Brabb, 1995a). In addition, the Chabot fault appears to be an east-dipping oblique normal fault that has placed Late Cretaceous and younger strata (doubled by the earlier thrusting) in the hanging wall down onto Jurassic and Early Cretaceous rocks in the footwall. Although, Crane (1995) has suggested that the Chabot fault is an overturned, east vergent thrust fault, we have found no evidence to support this interpretation.

Late Pleistocene and early Holocene deformation was predominantly west directed oblique thrusting, which is evident in the Fremont subzone. The Mission fault has 7.5 km of late Pleistocene and younger right-lateral offset where it cuts the Chabot fault north of Niles, and 1500 meters of vertical offset at Mission Peak based on projected offset of the Briones-Orinda contact. Farther north, the late Pleistocene transpressional regime reactivated old faults or created new faults in the San Pablo and San Leandro subzones. This is demonstrated by the cutting of late Pleistocene (Rancholabrean age) gravels in the Oakland hills as well as the geomorphic features of the Wildcat and other unnamed faults. Additionally, recent observations by us and others have documented at least one parallel strand 400 meters west of the creeping strand in the San Leandro area that cuts the most recent soil horizon along a west vergent oblique reverse fault.

Most of the historic offsets within the Hayward fault zone are well documented by Lienkaemper (1992) in his map of the creeping strand. In addition, several faults in the Fremont subzone are seismically active. Others in the San Pablo and San Leandro subzones may also be seismically active but are too close to the creeping strand to be distinguishable in the seismic record. More trenching and other studies are needed to determine the full extent of deformation along the Hayward fault zone, and where and how much ground rupture may take place in the future.

Summary

The Hayward fault zone is a broad zone of deformation, within which the style and location of deformation has changed through geologic time. This change in location and style has led to the development of different structures in different parts of the fault zone, herein called subzones. Faulting in historic time is concentrated near the western margin of the fault zone, except in the Fremont subzone where it diffuses into several sub-parallel faults as it joins the Calaveras fault. The zone as a whole has undergone at least 43 km of right-lateral offset and a large but still unmeasured amount of compressional deformation. As little as 3 km of the right-lateral offset has occurred on the creeping strand. More research is required to determine whether or not faults outside the creeping strand are as dangerous or more dangerous than the creeping strand itself. However, given the active seismicity and offset of recent soils along strands other than the creeping strand, it is probable that the hazard zone will contain more than just the creeping strand.

Sources of data

All of the geologic mapping for the Hayward fault zone is new, but we acknowledge our debt to previous workers who established the geologic framework. Data sources for geologic mapping in the fault zone within Contra Costa County are provided by Graymer, Jones, and Brabb (1994). In Alameda and Santa Clara Counties, the geologic reports by Radbruch (1969), Case (1968), Graymer and others (1994), Robinson (1956), Hall (1958), and Crittenden (1951) are especially relevant. Preliminary geologic maps by T.W. Dibblee of most of the 1:24,000 quadrangles are available in Open-File Reports of the U.S. Geological Survey (see references). The map and report by Lienkaemper (1992) provided some of the lines for the creeping strand of the Hayward fault, and they contain many references to previous work. Several students have done theses in the area; the ones by Haltenhoff (1978), Whiteley (1978), and Prowell (1974) are especially pertinent.

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