Dimensions of the Westside Groundwater Basin
San Francisco and San Mateo Counties, California

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In
Geology: Hydrogeology

by

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CERTIFICATION OF APPROVAL

I certify that I have read *Dimensions of the Westside Groundwater Basin, San Francisco and San Mateo Counties, California* by Erdmann H. Rogge, and that in my opinion this work meets the criteria for approving a thesis submitted in partial fulfillment of the requirements for the degree: Master of Science: Hydrogeology at San Francisco State University

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Abstract

The Westside Groundwater Basin is a coastal aquifer system located on the San Francisco Peninsula between Golden Gate Park and Burlingame. Since the beginning of the 20th century groundwater from the Basin has been used for drinking water and irrigation purposes. Unfortunately, the basin wide potentiometric surface has gradually declined and saltwater intrusion from the Pacific Ocean is threatening this fragile aquifer system. Several studies have looked at groundwater movement within the Basin (Boone, Cook and Associates (1987), Yates et al. (1990), Applied Consultants (1991), Geo/Resources Consultants (1993), Phillips et al. (1993), CH2Mhill (1997)); unfortunately, all of the studies assumed horizontal layering of the hydrostratigraphic units. However, recent studies indicate that tectonic deformation and intense folding has altered the stratigraphy trend of the Westside Basin close to the Pacific Ocean (Bonilla (1998), Barr (1999)). Accordingly, the purpose of this study is to delineate hydrostratigraphic units within the Westside Basin by using isotopic data in conjunction with general mineral water quality data, water level data, and geologic cross-sections to depict the subsurface hydrogeology of the system. Our results indicate that the upper part of the Merced Formation (sequences P through Z of Clifton and Hunter (1991, 1999)) forms the major hydrostratigraphic units where groundwater is extracted. In addition, thick clay layers, observed in well logs and identified in cross sections, were tentatively correlated with sequences W and S2. Difference in water chemistry and isotopic age indicate that these clay layers work as aquitards between the hydrostratigraphic units.

I certify that the Abstract is a correct representation of the content of this thesis

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Chair, Thesis Committee

Acknowledgements

The Westside Groundwater Basin has been of growing concern to San Mateo County Environmental Health Division. It was due to this concern that the idea for this thesis was brought up to me Gail Lee. I owe her as well as Dean Peterson for their support for this project in its infancy as well as for all the opportunities I have had so far at San Mateo County. I also want to say thank you to Brian Schroth for his initial advice and to my advisors Matthew LaForce and Raymond Sullivan for making it possible that I completed this project. Finally, I want to thank Daly City Water and Wastewater Department, San Bruno Public Works, California Water Service Company and San Francisco Water Department for making a wealth of data available to me.

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Chapter 1

Introduction

The Westside Groundwater Basin is located on the San Francisco Peninsula and extends in north-south direction from Golden Gate Park, in San Francisco, to northern Hillsborough and Burlingame (Figure1.1). The northern boundary is marked by a bedrock rise to the surface extending from the northeastern part of the Golden Gate Park to the western edge of the Richmond district. In the northeast the basin is bounded by bedrock outcrops of Mt. Davis, Twin Peaks and San Bruno Mountain. In the southwest the Westside Basin is bounded by the San Andreas fault. The western and eastern boundaries of the basin are open. Unfortunately, the southern boundary has not been precisely determined. However, Phillips et al. (1993) tentatively assigned a southern boundary in Millbrae due to an increase in clay content that was encountered in boring logs (Figure 1.1). Since then, this southern boundary has been used as the basin boundary in different reports (CH2MHill (1994, 1996, 1997), Luhdorff and Scalmanini (2002)). However, no further research has been conducted to either corroborate this boundary or properly determine it. Accordingly, the first purpose of this study is to define the southern boundary of the Westside Groundwater Basin. This boundary has been determined based on interpolation of available water level data, as well as, on existing bedrock elevation maps.

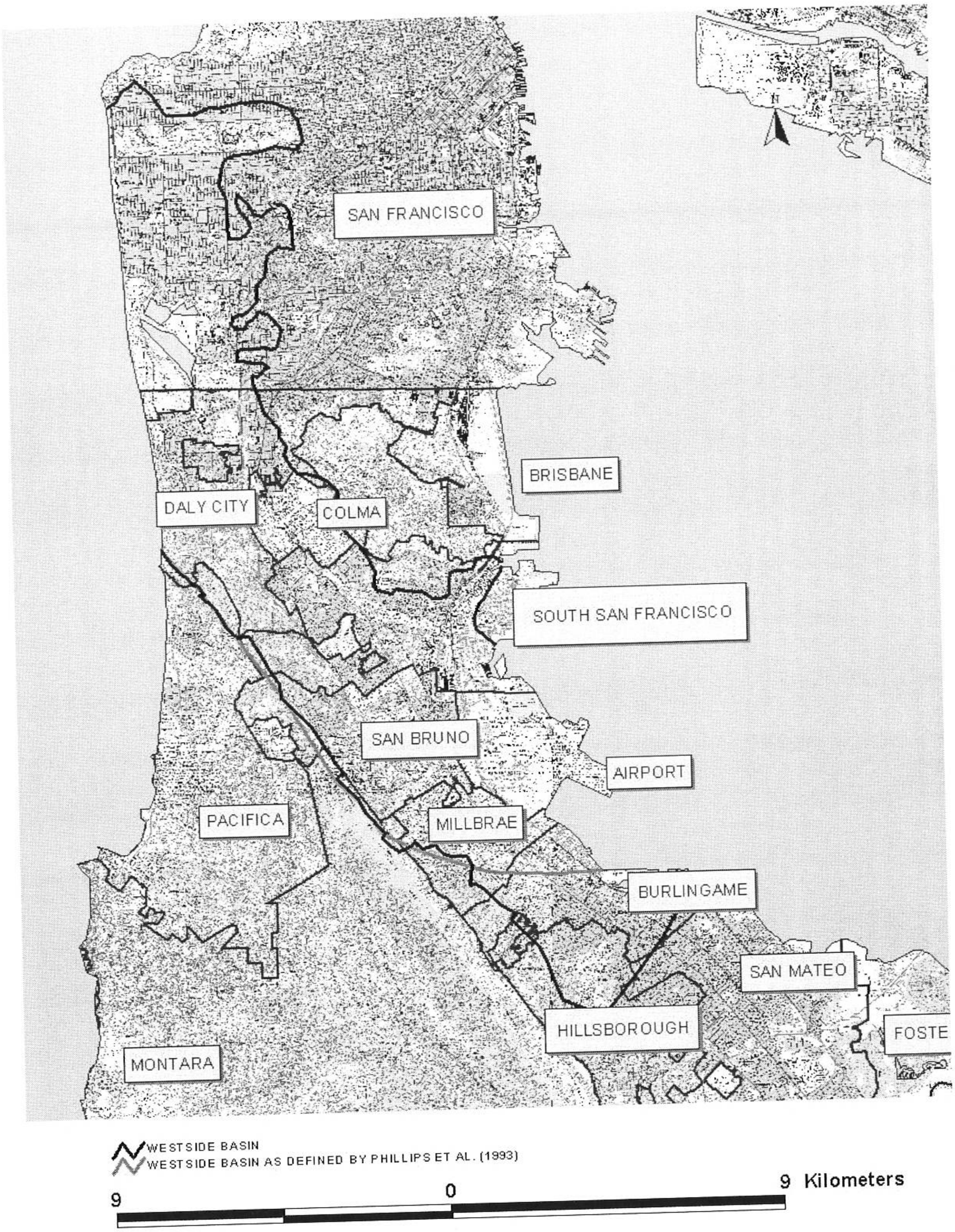


Figure 1.1: *Location of the Westside Groundwater Basin on the San Francisco Peninsula. Both basin boundaries as defined by Phillips et al. (1993) (light brown) and in this report are shown (black).*

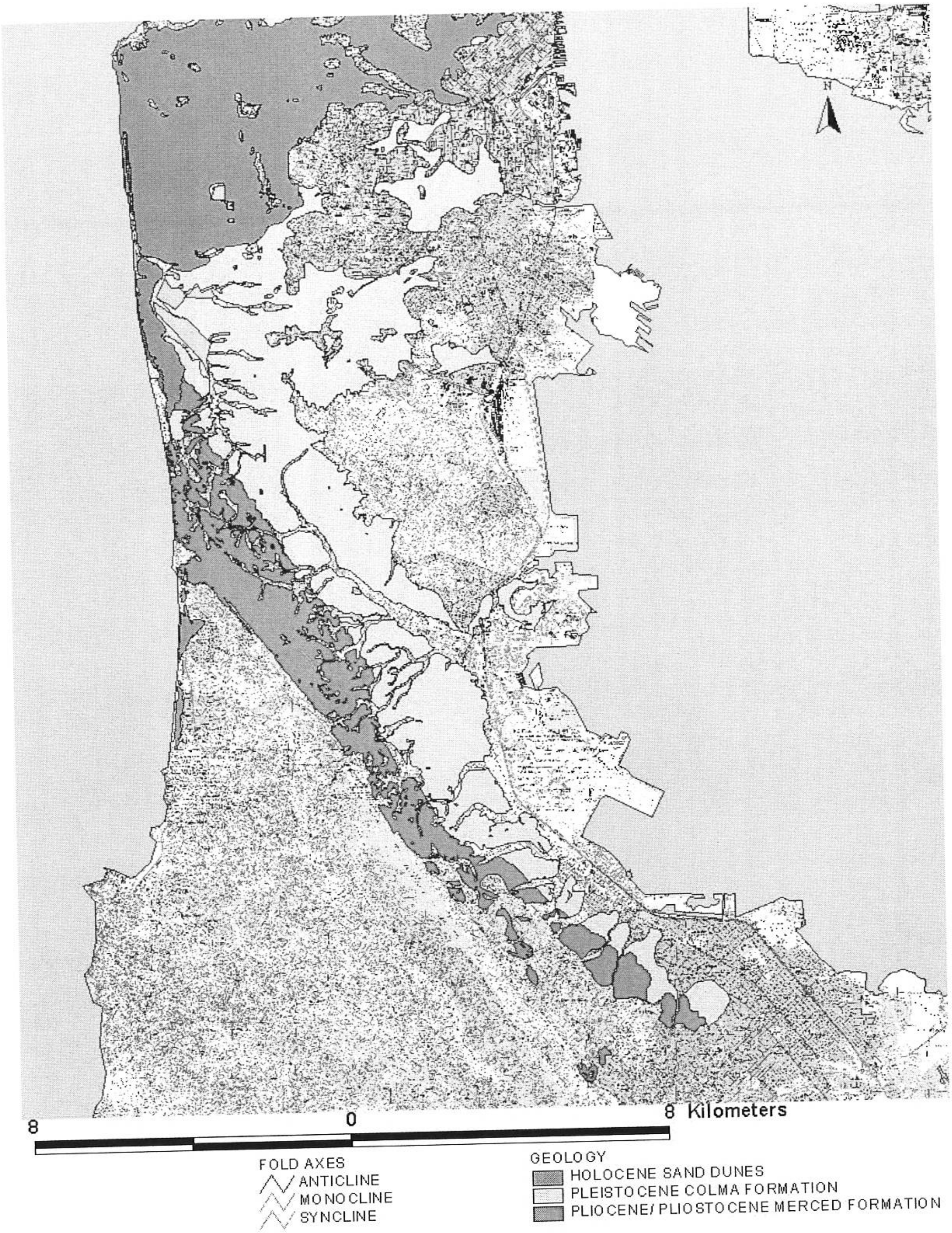


Figure 1.2: *Simplified surficial geology of the San Francisco Peninsula map after Blake et al. (2000), Bonilla (1998) and Brabb (1998) showing the location of the Merced Formation, Colma Formation and sand dunes.*

In the Westside Basin the main water bearing zones occur in the Merced (Plio-Pleistocene) and Colma (Pleistocene-Holocene) formations. The Merced Formation extends from Lake Merced to Burlingame. Outcrops of the formation can be found along the coastal bluffs in Daly City and Fort Funston and along the hills bounding the San Andreas and Serra faults (Figure 1.2). The Colma Formation lies over the Merced Formation (Clifton and Hunter, 1987, 1988, 1989, 1991, 1999) and, locally, directly on the Franciscan Complex (Hochstetler, 1973).

The Merced Formation has been well documented and characterized along the coastal bluffs in Daly City and Fort Funston by Clifton and Hunter (1987, 1988, 1989, 1991, 1999). These coastal exposures demonstrate the folded character of the Merced Formation between the San Andreas and Serra faults, which has also been documented by Pampeyan (1994) and Bonilla (1998). However, so far, no correlation between the coastal exposures and borehole descriptions for the sediments on the San Francisco Peninsula has been made. Furthermore, cross-sections through the Westside Basin (Kirker, Chapman & Associates (1972), Boone, Cook and Associates (1987), Applied Consultants (1991), Guidetti and Schaefer (1995), CH2MHILL (1996, 1997)) do not account for the folding of the Merced Formation west of the Serra fault. Thus, the second purpose of this thesis is to achieve a better understanding of the hydrogeologic characteristics of the Westside Basin via the construction of detailed geologic cross sections. I will attempt to correlate the different sequences of the Merced Formation along the coastal bluffs in Daly City with the sediments further inland on the San Francisco Peninsula. These cross sections will provide needed insight into structure and stratigraphy of the basin.

The presence of different clay layers that work as effective hydraulic barriers causes the Westside Basin to be multi-layered (Applied Consultants, 1991). The extent and location of these aquitards is also poorly understood. Therefore, based on the geologic correlation of the sediments of the Merced Formation throughout the basin an attempt is made to subdivide the Westside Basin east of the Serra fault into different hydrostratigraphic units. Available water quality data and isotopic data is also taken into consideration to further support this subdivision.

In summary, the goal of this thesis is to determine the horizontal and vertical extent of the Westside Basin. In order to achieve this (i) a detailed geological overview is presented, (ii) water level and water quality data is analyzed, (iii) cross sections are developed and (iv) isotopic data and historical land use information are included to corroborate the findings.

Chapter 2

GEOLOGIC SETTING

2.1 Stratigraphy:

2.1.1 Overview:

Different geologic formations are found on the northern part of the San Francisco Peninsula and many of these formations are found in the Westside Basin. Therefore, it is essential to have a thorough understanding of the geologic setting of the Westside Basin in order to be able to produce meaningful cross sections, properly interpret the geochemical data and understand the interconnection between water bearing zones. In this chapter the different geologic formations of the Westside Basin are presented and discussed. The main focus is set on the Merced and Colma formations, which are the main water bearing units. However, since water is also extracted from younger deposits such as sand dunes and alluvial deposits a discussion of these units is also presented. Landslide deposits and artificial fill, which can locally be found, will not be addressed here since they only influence the water table on a small local scale and do not further contribute to a regional understanding of the groundwater basin.

2.1.2. Statement of Problem:

Unfortunately, previous hydrogeologic studies (AGS 1995, Boone, Cooks and Associates 1987, CH2MHill 1994, 1996, 1997, Geo/Resource Consultants 1993, Guidetti and Schaefer 1995, Luhdorff and Scalmanini 2002, Phillips et al. 1993) on the Westside Basin failed to take into consideration the complex geology and tectonic setting of the basin. For example, it has been assumed that the unconsolidated sediments are either (i) horizontally layered (AGS 1995, Boone, Cooks and Associates 1987, CH2MHill 1994, 1996, 1997, Geo/Resource Consultants 1993, Guidetti and Schaefer 1995, Phillips et al. 1993), or (ii) tilted on the west side but flattening out towards the San Francisco Bay (Luhdorff and Scalmanini 2002). However, geologic studies in the area (Barr 1999, Bonilla 1959, 1965, 1971, 1998, Clifton and Hunter 1987, 1989, 1991, 1999, Kennedy 2002, Pampeyan 1994) show that these assumptions are not the case. Subsequently, I intend to conduct a detailed review of the existing literature on the geologic and tectonic setting, discuss the basin formation, elaborate on the sedimentology of the basin, and discuss tectonic influences on the hydrostratigraphy of the basin.

2.1.3 Franciscan Group

The Franciscan Complex forms the basement of the whole Westside Basin. It is part of the Coast Ranges Province of California; its southern boundary is near Santa Barbara and its northern extent stretches into southern Oregon (Page 1966). In California, the Franciscan Complex is bound to the east by the Great Valley Sequence and to the west by the San Andreas fault System. However, on the San Francisco Peninsula the Pilarcitos fault marks the western boundary of the Franciscan Complex (Wakabayashi 1992, 1999a, 1999b, Wakabayashi and Hengesh 1995). Blake et al. (1982, 1984) subdivided the Franciscan Complex in the San Francisco Bay Area into eight different, fault-bounded terranes. Of these eight terranes, three underlie the Westside Basin, the Marin Headlands, the San Bruno Mountain and the Central terranes (Figure 2.1). Within the Westside Basin, most of these terranes are covered by Neogene unconsolidated sediments. Outcrops of terranes are found at Mount Davis and Twin

Peaks (Marin Headlands terrane), San Bruno Mountain (San Bruno Mountain and Central terranes) and between the Serra and San Andreas fault from San Bruno south to Hillsborough (Central terrane).

Previous studies (Kirker, Chapman & Associates and Todd, D. K. 1972, Boone, Cook and Associates 1987, Yates et al. 1990, Phillips et al. 1993, CH2MHill 1994, 1996, 1997 and Luhdorff and Scalmanini 2002) assigned the Franciscan Complex a very low hydraulic conductivity compared to the overlying unconsolidated and porous sediments. Thus, it acts as a basement aquitard and also forms a horizontal boundary to the northeast of the Westside Basin. It is important to note that these studies assume negligible or no groundwater movement through the Franciscan Complex. Nevertheless, Burns and McDonnell (2002) showed that small, but significant groundwater flow through fractured rock does occur from the Franciscan Complex into the overlying unconsolidated sediments. They determined that fractures encountered in the Franciscan sandstone at the San Francisco International Airport allowed groundwater to percolate downwards and migrate into the Colma and Merced formations.

In light of these findings it is necessary to look into the geology of the Franciscan Complex with almost as much detail as one would look into the geology of the Merced and Colma formations. To date, Burns and McDonnell (2002) is the only investigation that has provided detail on the geologic and hydrogeologic characteristics of the Franciscan Complex within the Westside Basin. Unfortunately, this research has been restricted to the Franciscan sandstone, which underlies most of San Francisco International Airport.

Structure and Composition:

The Franciscan Complex is composed of a wide variety of sedimentary, volcanic and metamorphic rocks. The sediments, mostly sandstones, conglomerates, shales and chert, were deposited in the Pacific Ocean on top of oceanic basalt of the former Farallon Plate between the Thitonian and the Cenomanian (Seiders 1988, Elder 1999). As the Farallon Plate moved east, it was subducted under the North American Plate, where it was thermally overprinted (Underwood et al. 1999), producing metamorphic rocks ranging from metasediments formed under zeolite and prehnite-pumpellyite-grade metamorphism (Underwood et al. 1999) to serpentinite and blueshist formed under blueshist-grade metamorphism (Wakabayashi 1995). During the subduction process slivers of the Farallon plate were thrusted off and accreted to the North American Plate forming a zone of amalgamated tectonostratigraphic terranes (Elder 2001). Consequently, a stacking sequence formed where the structurally higher rocks to the east are older and each overthrusted wedge to the west is younger (Wakabayashi 1992, 1999, Elder 2001).

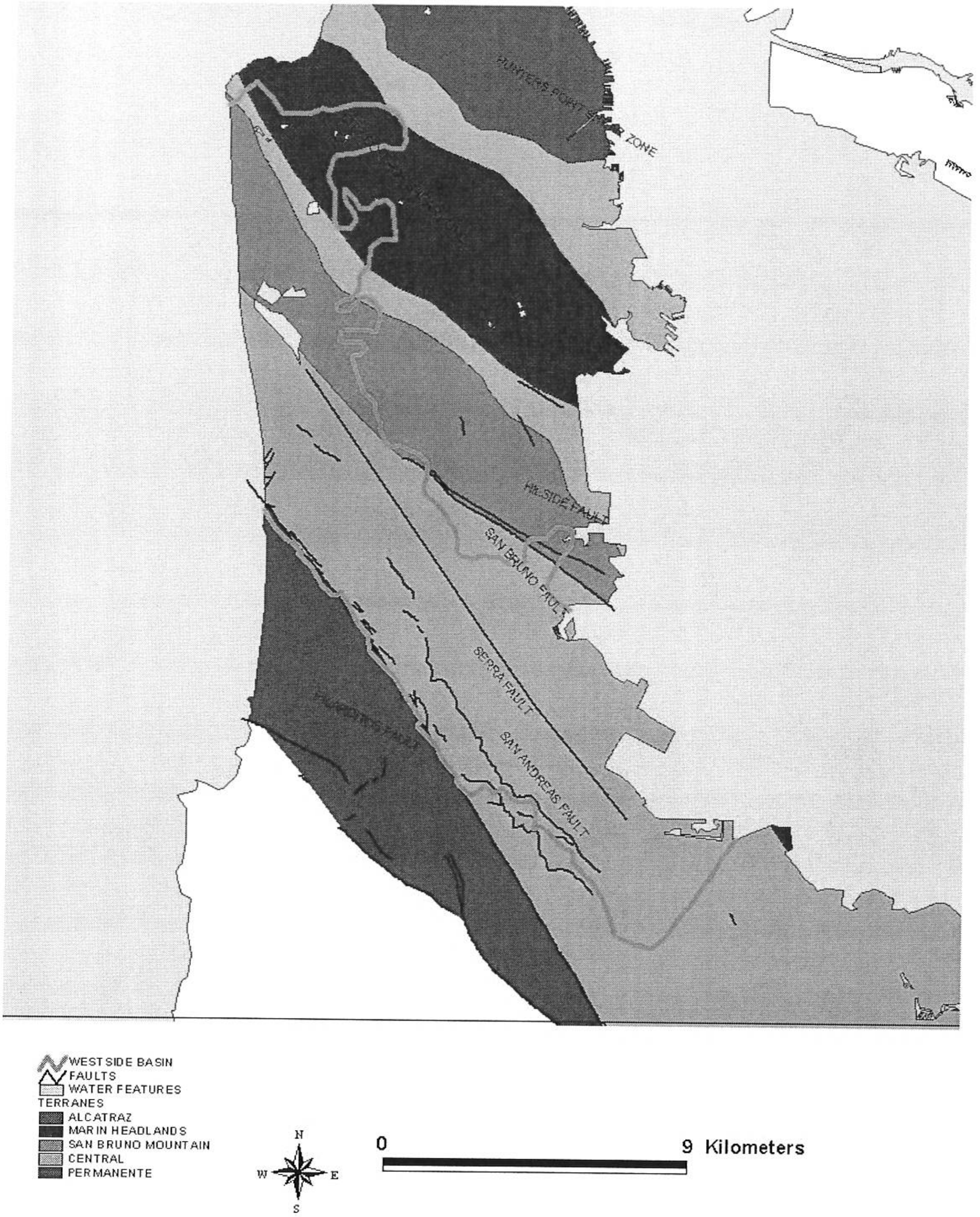


Figure 2.1: *Franciscan terranes located within the Westside Basin. Each of these terranes is separated from another by a fault or a shear zone composed of Franciscan mélange. Compiled from maps by (Underwood et al. 1999, Wakabayashi 1999 and Elder 2001).*

Terranes of the Westside Basin:

The structurally oldest terrane within the Westside Basin is the Marin Headlands Terrane, followed by the San Bruno Mountain Terrane and the Central Terrane (Figure 2.1). The Marin Headlands Terrane is composed of a basaltic crust covered by chert and sandstone (Elder 2001). Based on fossils found in both the chert and sandstone Murchey and Jones (1984) determined the chert to be between 200 and 100 million years old (Lias through Albian) and the sandstone to be between 100 and 90 million years old (Albian and Cenomanian). The San Bruno Mountain Terrane is composed predominantly of sandstone but its age is unknown due to its lack of fossils (Blake et al. 2000, Elder 2001). Wakabayashi (1992) suggested the sandstone within the San Bruno Mountain Terrane might be Campanian in age. The Central Terrane is also composed mostly of sandstone (Pampeyan 1994, Underwood et al. 1999) but the age of the sandstone is also unknown. Burns and McDonnell (2002) studied the general trend of fractures in the sandstone of Central Terrane and observed that they mostly strike either north-south or northwest-southeast and dip to east or northeast at angles ranging from 45° to 90°.

2.1.4 Pliocene and Pleistocene Deposits:

2.1.4.1 Merced Formation:

From the hydrogeologic point of view the Merced Formation is the most important geologic formation within the Westside Basin. The majority of the hydrostratigraphic units can be found in the Merced Formation, as it is composed of several major sand and clay beds. Consequently, it is of extreme importance to accurately describe the lithologic and stratigraphic characteristics of the Merced Formation as well as get a thorough understanding of the environmental and tectonic setting in which the Merced Formation was deposited.

Lawson (1893) first defined the "Merced series" as a thick succession of only partially indurated fossiliferous marine sands and sandy silts of late Cenozoic age, which crop out in a northwest trending belt south of San Francisco. He named the formation exposed at the sea cliffs at Fort Funston and Thornton Beach State Park after Lake Merced. The formation is largely restricted to a 3-km-wide structural basin between the San Andreas fault on the southwest and the covered, poorly known and disputed San Bruno fault to the northeast (Bonilla 1971, Schlocker 1974, Brabb and Pampeyan 1983, Hunter et al. 1984) (Figure 1.2). This basin is about 1000 meters at the coastal bluffs and merely 60 meters deep in Burlingame (Brabb 1993). The exposures stretch continuously for at least 21 kilometers from Lake Merced to Burlingame and discontinuous as far south as Hillsdale Boulevard in San Mateo (Pampeyan 1994). About 1,750 meters of Merced sediments crop out for about 6 km in a well-exposed tilted sequence in sea cliffs from Mussel Rock till just north of Lake Merced (Clifton et al 1988, Clifton and Hunter 1989, 1991, 1999). Of these 1,750 meters the northernmost 400 meters were deposited in a mainly terrestrial environment and the subsequent 1,350 meters to the south mostly in a marine setting (Clifton and Hunter, 1988) (Appendix C). Clifton et al. (1988) subdivided the Merced Formation into 40 parasequences (Appendix C), which allows a better correlation of the various units. This sequence subdivision has also been used in this report.

Composition:

Sediments of the Merced Formation are primary composed of sands and clays, and to a minor degree gravel. The amount of each of these grain sizes in a bed is directly dependent on the environment in which they were deposited. The bedrock elevation map by Brabb (1993) indicates that bedrock is encountered along the coastal bluffs in Daly City at a depth of 1,000 meters and consequently the exposures found there represent only a fraction of the sediments of the Merced Formation. All that can be said, based on Clifton and Hunter's (1989, 1991, 1999) description of the exposures along the coastal bluffs in Daly City, is that sands predominate in the upper 400 meters of the formation (above sequence J) where the sediments are mainly terrestrial in origin (Clifton and Hunter 1989). On the other hand, the amount of clays generally increases downwards along the exposed section of the Merced below sequence J, in the more marine part of the succession.

- Lower Part of the Merced Formation:

Based on the mineralogical composition the sediments of the lower part of the Merced Formation are derived mostly from local Franciscan source (Hall 1965). Indicator minerals for the Franciscan Complex are glaucophane, pumpellyite, lawsonite, tremolite-actinolite and epidote, which are common among the heavy mineral suite of the lower Merced Formation. These minerals occur in Franciscan glaucophane schists and related metamorphic rocks. In addition, epidote may have originated from Franciscan sandstone. Albite could have come from veins cutting Franciscan sandstone, from detrital grains in the sandstone, from albite-rich Franciscan metamorphic rocks such as jadeitized graywackes, and from albitized Franciscan volcanic rocks such as spilites and keratophyres. The rare occurrence of augite and hypersthene could have been derived from basic volcanic rocks in the Franciscan (Hall 1965). The granodiorite of the Montara Mountain is a probable source for the less than 1% K-feldspar and oligoclase found in the lower part of the Merced Formation (Hall 1965).

- Upper Part of the Merced Formation:

In contrast to the lower part of the Merced Formation, the mineralogical composition of the upper part of the Merced Formation indicates a sediment provenance in the Sierra Nevada (Hall 1965). Franciscan detritus is almost entirely absent from the upper part of the Merced Formation and Colma Formation. The average composition of the heavy mineral suite of this part of the succession is 54% hornblende, 18% hypersthene and 15% augite. This suggests that the most likely source of these materials are the Mehrten Formation and the Tuscan Formation (Miocene to Pliocene) in the Sierra Nevada (Hall 1965).

Stratigraphy:

The lithology of different units of the Merced Formation varies considerably, reflecting different depositional environments of the formation. Overall, the stratification ranges from finely laminated to very thickly bedded. Locally, cross-stratification occurs, particularly where gravel is present, and, in places, lamina are contorted (Bonilla 1959). The bedding thickness of the strata averages 30 centimeters; though it ranges from a fraction of a centimeter to 9-meter thick zones (Bonilla 1959). In a few places false stratification due to color banding occurs, which may be at any angle to the true stratification. Utilizing these stratigraphic variations, Clifton and Stagg (1986), Clifton and Hunter (1989, 1991,1999) and Clifton et al. (1988), Hunter (1982) and Hunter et al. (1984) were able to subdivide the Merced Formation into 40 sequences (sequence LL at the bottom and Y at the top) (Table 2.1) based on transgressive/regressive cycles they observed along the cliff exposures between Mussel Rock and Fleischhacker Zoo. In the lower part of the Merced Formation the individual transgressive/regressive cycles are thicker than those in the upper part. The individual transgressive/regressive cycles reflect eustatic sea-level fluctuations that occurred during Pleistocene time. The general pattern of transgression and regression can be fairly well matched in much of the section to a Pleistocene sea level curve determined from oxygen isotope data (Clifton et al. 1988).

The most common pattern observed at the coastal bluffs is one of upward shallowing and coarsening of sequences (regression). The landward translation of a shoreface (transgression) tends to cause the nearshore, foreshore and any nonmarine deposits associated with the retreating beach (transgressive deposits) to be eroded (Bruun 1962, Ryer 1977). The hiatus produced by this phenomenon is generally marked by a lag deposit of pebbles and shells or well-sorted non-marine deposits containing root structures or other evidence of subaerial exposure on the bottom. This transgressive lag deposit is followed upwards by an abrupt change to muddy sediment of deeper water facies that contain marine mollusks. In many of these transitions, a thin lignitic or peaty layer separates sand and mud. Typically, the muddy sediment becomes progressively coarser upsection, culminating in crossbedded sand and gravel that contain numerous shell fragments (regression). Nearly all of the transgressive intervals in the Merced Formation show such a transgressive surface of erosion, and the facies involved in the upward deepening differ among the cycles (Clifton and Hunter, 1989, 1991, 1999).

The transgressive/regressive cycles have so far only been described along the coastal bluffs at Fort Funston and in Daly City. Bonilla (1959) identified unit S2, containing the Rockland Ash at several locations in the Westlake District and Clifton and Hunter (1987) identified sequence U at the Olympic Country Club. The identification of the various sequences of the Merced Formation is even more complicated in most of the area east of Highway 280, where the Merced Formation is covered by the Colma Formation and Holocene deposits. At the San Francisco International Airport various sand and clay layers have been identified in borings and monitoring wells. There, sand layers have been grouped into zones named from top to bottom A, B and C, respectively. The A sand is believed to represent young alluvial deposits. The B sand has been correlated with the upper part of the Colma Formation. The C-Sand Zone, composed of intercalated silty and clayey sands and sand, is believed to be equivalent to the lower part of the Colma Formation and the upper part of the Merced Formation (Versar-Sierra EnviroGroup 1995).

Versar-Sierra EnviroGroup (1995) noticed significant differences in depth to bedrock among monitoring wells at the San Francisco International Airport. They suggested that the C-Sand Zone may not extend east of the bedrock high located between the main Airport terminal and the Maintenance Operation Center (MOC). At Plot 1 the bedrock appears to be less than 60 meters in depth, thereby cutting off the C-Sand Zone (Appendix 1, cross section C-C').

Within the Merced Formation paleosols can be found at several horizons. Almost all of the paleosols show root structures. Paleosols also occur in association with lignitic mud overlying alluvial deposits. In general, the paleosols are well developed in the backshore facies in the upper 200 meters of the Merced Formation, but are poorly developed in the same facies in the lower part of the succession (Clifton et al. 1988). Hochstetler (1973) described that the contact between the Merced and Colma Formations is marked by an approximately 5 cm thick paleosols with limonite-rich clay and mica.

Structure:

The Merced Formation strikes to the northwest, ranging from N 30° W to N 80° E but mostly between N 40° W and N 50° W, and dips to the northeast almost everywhere in the cliff exposures. Dips in the Merced Formation in the Westlake District are to the northeast and range from 10° to 80° (Bonilla 1959). Along the coastal bluffs the dips are steeper in the south, adjacent to the San Andreas fault, and gradually become lower to the north. They can be as low as 2° or 3° close to John Daly Boulevard. North of John Daly

Boulevard the dips become steeper again. Bonilla (1959, 1998) suggested that this change in attitude of the strata could be seen as a structural terrace formed by an anticline and a syncline that trends northwest or west-northwest and passes near the intersection of John Daly Boulevard and Skyline Boulevard. He also attributed the change in fossil fauna at John Daly Boulevard and Skyline Boulevard observed by Louderback (1951) to be related to a possible period of nondeposition or an unconformity in the stratigraphic sequence. Further inland in Daly City and South San Francisco Bonilla (1998) recognized several synclines and anticlines that are shown on his geologic map of the San Francisco South 7.5 minutes Quadrangle (Figure 1.2).

Further south, in San Bruno and Millbrae, Pampeyan (1994) shows on his geologic map of San Mateo and Montara Mountain 7.5 minutes Quadrangles varying dips in the Merced Formation both to the northeast and the southwest. This is related to the folding and faulting of the Merced Formation between the Serra fault and the San Andreas fault (Figure 1.2). East of the Serra fault the Merced Formation seems to be tilted to the northeast, as measurements off Berkshire Drive in Millbrae indicate. Similar trends are also observed in the Colma Formation at Cedar Avenue and Hickory Avenue and at Jenevein Avenue and Cunnigham Way.

Age:

Since the Merced Formation was first dated (Blake 1858) different ages have been assigned to the Merced Formation. Based on firmly indurated Merced concretions containing *Scutellaster interlineata* Blake (1858) assigned the Merced Formation to the Tertiary. Whitney (1865) and Cooper (1888) dated outcrops of the Merced Formation along the sea cliffs as Pliocene. Ashley (1895) provided the first detailed fossil listing of the type Merced. He separated the strata above the base of the "upper gastropod bed" (in sequence R) from the rest of the Merced Formation on the basis of their modern fauna and tentatively assigned them to the Pleistocene. Arnold (1906) and Martin (1916) also assigned the type Merced Formation to the upper Pliocene and lower Pleistocene. Steward and Steward (1933) described the Foraminifera in the Merced Formation and documented a change in microfaunal population in the vicinity of the Thornton Beach landslide (in sequence R?).

Glen (1959) provided the first systematic description of the megafaunal distribution of the Merced Formation and like Ashley (1895) divided the type Merced section into an upper member of Early Pleistocene age, which lies in apparent unconformity over a lower member that he correlated with the San Joaquin Formation of late Pliocene age. He informally called the beds that outcrop between the 1906 trace of the San Andreas Rift and the Merced-Franciscan contact at Mussel Rock the "lowermost Merced" and correlated them with the Etchegoin Formation of Middle Pliocene age.

Hall (1965) examined the mineralogical composition of the Merced Formation and noticed a change in provenance near the top of sequence P from local Franciscan derived material (lower part of the Merced Formation) to Sierran derived material (upper part of the Merced Formation) (Table 2.2). The change in mineralogical composition reflects the change in drainage of the Sacramento-San Joaquin River system from the Monterey Bay to the Golden Gate. This change in drainage is dated roughly at 0.6 million years (Sarna-Wojcicki et al. 1985).

Hall (1965) pointed out that marine megafossils below sequence P correlate with the San Joaquin Formation, which is Blancan age (4.5 to 1.7 million years). About 90 meters above the mineral change occur remains of *Mammuthus* (top of sequence R), *Tanupolama* (sequence U), *Megalonyx* (base of sequence T), *Equus* (sequence U), and antilocaprid (top of sequence T), all of Irvingtonian age (1.7 to 0.2 million years). A few meters above the *Mammuthus* locality occurs a hornblende bearing tuff (Rockland Ash at the top of sequence S_2), which has been dated as 0.4 million years by K-Ar method (Sarna-Wojcicki et al., 1985) (Table 2.1). Although recent work by Lampherer (1999) assigns an age of 0.61 million years to the Rockland Ash, strontium isotopic composition of *Elphidiella hannai* for various sequences of the Merced Formation (Ingram and Ingle 1998) do support an age of 0.4 million years for the Rockland Ash.

Evidence for a Pleistocene age is the occurrence of the echinoid *Scutellaster major* (Kew) in the lower Merced (Clifton et al. 1988). According to Roth (1979) *Scutellaster major* occurs from 60 meters below to 250 meters above the trace of the San Andreas fault (Table 2.1). If the range of *Scutellaster major* in the Merced Formation is similar to its range in the Eel River Basin, part of the type section of the Merced north of the trace of the San Andreas fault must be entirely of Pleistocene age. Unfortunately, *Scutellaster major* has not been identified elsewhere than in the Eel River Basin and in the Merced formation, and therefore its stratigraphic significance in the Merced Formation must be regarded as questionable (Clifton et al. 1988).

Ingram and Ingle (1998) determined the strontium isotopic composition of the foraminifera *Elphidiella hannai* for various sequences of the Merced Formation (Table 2). Although the age resolution for the lower Merced Formation is not precise due to little variation in the $^{87}Sr/^{86}Sr$ ratio in global seawater between 2.4 and 4.3 million years, the base of the exposed section of the Merced Formation in the coastal bluffs in Daly City can be constrained to 2.4 to 4.8 million years. This age determination for the lower part of the Merced agrees with Pampeyan (1994) who described molluscan fossils of late Pliocene age to be common in the area from San Bruno to Burlingame. He states that the Pleistocene part of the Merced Formation was not recognized in that area.

Clifton et al. (1988) generated a model of Pleistocene global sea levels based on an oxygen-isotope record. They assumed that all of the $^{18}O/^{16}O$ changes were the result of eustatic sea-level fluctuations. Based on this assumption and using published oxygen isotope values (Shackleton and Opdyke 1976) they produced a sea level-versus-depth curve. This depth curve was converted to age using the oxygen-isotope stage/paleomagnetic boundary age model of Pisias and Moore (1981). They observed 23 age datums that are evenly distributed between 11,000 and 1.82 million years. In the absence of better age control, it was difficult for them to correlate individual transgressive-regressive cycles observed in the Merced cliff exposures with specific derived sea-level oscillations. The only well-established tie is the Rockland Ash (top of sequence S) dated at 0.4 million years. Following the deposition of the ash, this location was inundated to the extent that nearshore deposits accumulated. It is possible that this transgression may correspond to the small rise in sea level that began at approximately 0.39 million years (Clifton et al. 1988). Five transgressive and regressive cycles can be observed between the Rockland Ash (top of sequence S) and the base of the Colma Formation (sequence Z). Clifton et al. (1988) concluded that the Colma Formation most likely was deposited during the last interglacial, the Sangamon. This agrees with Hall's (1965, 1966) and Hochstetler's (1973) findings. The Sangamon now corresponds to oxygen-isotopic stage 5, dated at 0.07 to 0.13 million years, or to one of the substages of stage 5 (Shackleton and Opdyke 1973, 1976, Pisias and Moore 1981). Consequently, the top of the Merced (sequence Y) is probably older than 0.2 million years (Clifton et al. 1988).

1.Rockland Ash:

The Rockland Ash (top of sequence S_2) was first noticed along the cliff exposures at Fort Funston by Lawson in 1893. It comes from an eruption near Lassen Peak, about 185 miles to the northeast (Clifton and Hunter 1999). Several attempts have been done to date the age of the Rockland Ash by means of fission track and potassium-argon analysis (Hall 1965, Gilbert 1969, Sarna-Wojcicki et al. 1976, Sarna-Wojcicki et al. 1977, Sarna-Wojcicki et al. 1985, Meyer et al. 1991, Lampherer et al. 1999). The age of the ash ranges from 1.5 to 0.4 million years. The most commonly accepted date nowadays is 0.4 million years (Sarna-Wojcicki et al. 1985).

Bonilla (1959) found during grading operations for the housing tract of the Westlake District a bed of friable volcanic ash about a foot thick near the intersection of Westmoor Avenue and Skyline Boulevard. The ash, exposed intermittently for 760 meters northwest of the intersection, is clean, white, fresh to moderately weathered, and is made up mostly of sharp fragments of volcanic glass, with very rare diatom fragments. Bonilla (1959) correlated this ash with the Rockland Ash. He also found other exposed ash bed locations. One of them, close to the intersection of 87th Street and Pinehaven Drive, is about 1.8 meters thick and probably is the same zone as the ash and diatomaceous earth zone that crops out along Eastmoor Drive about 640 meters west of Junipero Serra Boulevard, and is also probably equivalent to the thick ash that crops out southwest of Lake Merced. Bonilla (1959) did not correlate these ash beds to the Rockland Ash. However, the glass in nearly all ash samples from 10 localities near Lake Merced and Westlake areas had a refraction index of 1.50, and a maximum index of 1.51. This suggests a similar provenance for all ash outcrops, and, therefore, it is possible that all ash outcrops in the Westlake District and Lake Merced area are those of the Rockland Ash. It is important to note that more recently another Rockland Ash locality was found at the Olympic Country Club by Barr (1999).

The Rockland Ash has also been found in areas other than near Lake Merced and the Westlake District. Atwater et al. (1977) described the presence of the Rockland Ash in a borehole about 1,200 meters east of the mouth of Islais Creek Channel. The ash occurs 20 meters below the bottom layers of the Old Bay Muds. Furthermore, Sarna-

Wojcicki and others (1985) identified another outcrop of the Rockland Ash imbedded in the upper part of the Santa Clara Formation in Woodside. Pampeyan (1994) suggests that this outcrop of the Rockland Ash confirms Addicott's (1969) assumption that the Merced Formation is the temporal marine equivalent of the Santa Clara Formation.

Depositional Environment and Development of the Basin:

Most of the sediments of the Merced Formation accumulated in a relatively small structural basin that probably developed between the San Andreas and San Bruno Mountain. No evidence exists within the sediments exposed in the sea cliff section for deposition within a topographic trough (Clifton and Hunter 1999). A small part of the Merced Formation (lowermost Merced) can be found east of the San Andreas fault at Mussel Rock. This suggests that the Merced Formation was deposited over a somewhat larger area than that in which the current exposures are found (Hunter et al. 1984). Part of the basin is located under the Pacific Ocean. Offshore gravity, magnetic, and seismic surveys do not indicate whether the basin is intact or broken into a series of smaller slivers (Cooper 1973, McCulloch 1987 and Clifton 1989). The basin seems to be more than 1,000 meters deep where it crosses the shoreline in Daly City, but shallows about 4 km to the southeast to less than 200 meters (Bonilla 1964).

The Merced Formation appears to have been deposited in a paralic setting (Clifton and Hunter 1999) and the depositional basin could have been either a local arm of the sea developed along the present San Andreas rift or a channel connecting an early San

Francisco Bay drainage system to the Pacific Ocean (Crandall 1907). Hall (1965) also stated that the Merced's basin might have been the former route of drainage from San Francisco Bay. The sediment exposures along the coast in Daly City indicate an open coast setting with no highland to the west (Clifton and Hunter 1999).

The Merced Formation was deposited during a series of transgressive/regressive cycles with a shoreline trending between north and northwest (Chiocci and Clifton, 1992). During regression, the dominant coastal morphology seems to have been a prograding strand plain without significant embayment. In contrast, the transgressions seem consistently to have produced a barrier coastline with extensive back barrier lagoons or estuaries encroaching over an adjacent nonmarine coastal plain. The progressive upward coarsening of the inferred lagoonal deposits suggests an approaching barrier, and the crossbedded sand and gravel can be attributed to migrating tidal inlets (Clifton and Hunter 1999).

Ten depositional facies types can be delineated: outer-shelf, mid-shelf, inner-shelf, nearshore, foreshore, backshore, aeolian dune, alluvial, marsh/pond/swamp, and coastal-embayment facies (Clifton et al., 1988). The presence of these facies in the section is the result of the occurrence of transgressive/regressive cycles. The origin of these cycles in the Merced is uncertain. Although they appear generally similar in scale and duration to the known Pleistocene glacio-eustatic sea level fluctuations, tectonic and sedimentologic influences cannot be precluded (Clifton and Hunter 1999). In fact, the presence of sand rods, shells and sand dikes aligned in a north-northeast direction parallel to the strike of extensional fractures as well as laminar lensed intervals in the various strata do further corroborate the subsiding characteristic of the basin (Clifton and Hunter 1991).

In the lower 1,300 meters of section (below sequence J), the pattern of transgression and regression is generally larger than in the upper 450 meters. The lower 1300 meters are dominated by shelf facies, and a presence of a shoreline seems to occur mostly at or near relative low stands of the sea (Clifton and Hunter 1999). This suggests that the rate of sedimentation generally kept pace with the rate of subsidence (Clifton and Hunter 1987). The rate of accumulation (and rate of subsidence) in this part of the section is about 1 to 1.5 meters per 1,000 years (Clifton et al. 1988). This rate of subsidence seems to have prevailed till the deposition of the Rockland Ash (top of sequence S_2) 0.4 million years ago. The increase in the average thickness of the transgressive/regressive cycles in the lower part of the section (below sequence J) may reflect a greater rate of subsidence in the early phase of basin development (Clifton et al. 1988).

The upper 300 meters of the section are dominated by non-marine facies. This suggests that the presence of a shoreline seems to be associated with relative high stands of the sea. The change in facies may be due in part to diminished subsidence rates (0.8-0.9 meters per 1,000 years), but probably reflects an increase in the rate of sedimentation resulting from a major change in provenance from local Franciscan sources to the Sacramento-San Joaquin River systems that occurs in the upper part of sequence P (Hall 1965, 1966, Clifton and Hunter 1987, 1989, Clifton et al. 1988).

The presence of gravel in nearshore deposits throughout the succession suggests that high gradients were maintained over the entire period of deposition. The abundance and grain size of gravel in the nearshore facies declines in the section below sequence VV, possibly reflecting lower stream gradients and/or diminishing discharge. The patterns of transgressions and regressions, however, seem uninfluenced by any such change (Clifton et al. 1988).

Several authors including Louderback (1951), Trask and Rolston (1951), Addicott (1969), Sarna-Wojcicki (1976), Sarna-Wojcicki et al. (1977), Atwater et al. (1977), and Hunter et al. (1984)) noted that the distribution of the Merced Formation beneath San Francisco Bay is poorly known. All that is known is that some beds equivalent to the upper part of the Merced occur locally beneath San Francisco Bay. Apparently, present San Francisco Bay was not a depositional basin while the lower part of the Merced was accumulating (Atwater et al. 1977, 1981, Hunter et al. 1984). This observation agrees with Christensen (1966) statement that on the San Francisco Peninsula throughout the Pliocene and most of the Pleistocene the ranges have risen repeatedly while the basins have rather steadily subsided.

The upper boundary of the Merced Formation was determined by Hall (1966) who identified that sequence Z (Colma Formation) truncates the contact between sequence Y and sequence X (Merced Formation). This unconformity indicates that the basin changed dramatically before deposition of the Colma Formation about 0.13 million years ago. Meyer et al. (1991) noticed a 30° declination anomaly in the magnetization pattern of the Rockland Ash after correction for tilting of the Merced Formation. They noted that the magnetization of the Rockland Ash probably occurred prior to the folding of the Merced Formation. Rotational uplift due to low angle faults associated with movement on the nearby San Andreas fault and erosion followed the deposition of sequence Y in the period of 0.2 to 0.13 million years. Uplift and tilting of the Colma Formation to elevations of about 180 meters south of Lake Merced suggests that this deformation may be ongoing today (Clifton et al. 1988).

It is not clear whether the tilting and folding of the Merced Formation started in the interval between deposition of the Merced and Colma formations (Clifton et al. 1988) or if it already started before that. A possible early but short-lived episode of emergence that may be related to tectonic uplift is suggested by the dissected surface that separates sequences T and U (Hunter et al. 1984).

Recent faulting can be observed in the lower part of the Merced Formation. There the strata are cut by small, vertical, apparently right-lateral strike-slip faults that parallel the San Andreas fault and that are offset only a few meters (Clifton et al. 1988). These faults seem to postdate the folding of the strata and probably occurred within the last 20,000 years (Clifton and Hunter 1999). The orientation of these faults has a wide range and varies from an east-west or east-southeast to a west-northwest direction (Clifton et al. 1980). The section appears to be structurally continuous, although the possibility of significant offset by hidden faults at the few places where the section along the cliffs is unexposed cannot be precluded (Clifton and Hunter (1987)).

The lowermost part of the Merced Formation, which is on the southwest side of the San Andreas fault, contains a fossil fauna that mostly differs from the fossil fauna of the rest of the Merced Formation in Daly City, north of the San Andreas fault (Addicott 1969, Hunter et al. 1984). Addicott (1969) suggested that this part of the Merced Formation correlates with marine Pliocene strata of the Santa Clara Formation in Woodside and was displaced along the San Andreas fault (Figure 2.2).

The relationship of the contact between the lowermost Merced and the Franciscan basement is also unclear. While Higgins (1961) mapped the contact as a fault, Kleinfelder (2001) described the contact as an unconformity with the Merced Formation dipping 20 degrees to the northeast.

The Merced and Colma formations have been complexly folded between the San Andreas and Serra faults (Bonilla, 1998). Christensen (1966) was the first to notice this deformation. The scale of deformation increases from the northwest to the southeast. At Fort Funston and the Olympic Country Club, the Serra fault occurs as a blind fault indicated by an anticline (Barr 1999, Kennedy 2002). In that area only one syncline and anticline is present in the onshore section of the Merced Formation (Bonilla 1998, Barr 1999). South of the Broadmoore District the Serra fault already has a surface expression and at least two sets of synclines and anticlines are present (Bonilla 1998). In San Bruno, Millbrae and Burlingame the Serra fault is composed of a set of thrust faults that place Franciscan basement over the Merced and Colma formations (Pampeyan 1994).

2.1.4.2 Colma Formation

The Colma Formation, of Pleistocene age, is another major formation from the hydrogeologic point of view within the Westside Basin. As shown later in chapter four, it comprises at least one hydrostratigraphic unit. The Colma Formation crops out mainly in the valley that extends from Lake Merced to San Bruno and underlies much of the alluvial plain southeast from San Bruno, at least as far south as Burlingame and possibly to San Mateo, and the sand dunes in western San Francisco (Bonilla 1959, Schlocker 1974, Pampeyan 1994) (Figure 1.2). It lies unconformably on the Franciscan Complex and the Merced Formation, and is unconformably overlain by alluvium, dune sand, and bay mud. The greatest thickness of sediments of the Colma seen in a single outcrop is roughly 23 meters; the total thickness of the formation is not known, but it may be as much as 60 meters (Bonilla 1959). It consists mainly of poorly consolidated sands, which were deposited on a variety of environments ranging from coastal marine to continental (Hochstetler 1973). Where the Colma Formation lies on the Merced Formation, it is difficult to distinguish one formation from the other since the mineralogical composition and grain size of the upper part of the Merced Formation and of the Colma Formation are similar (Schlocker 1974).

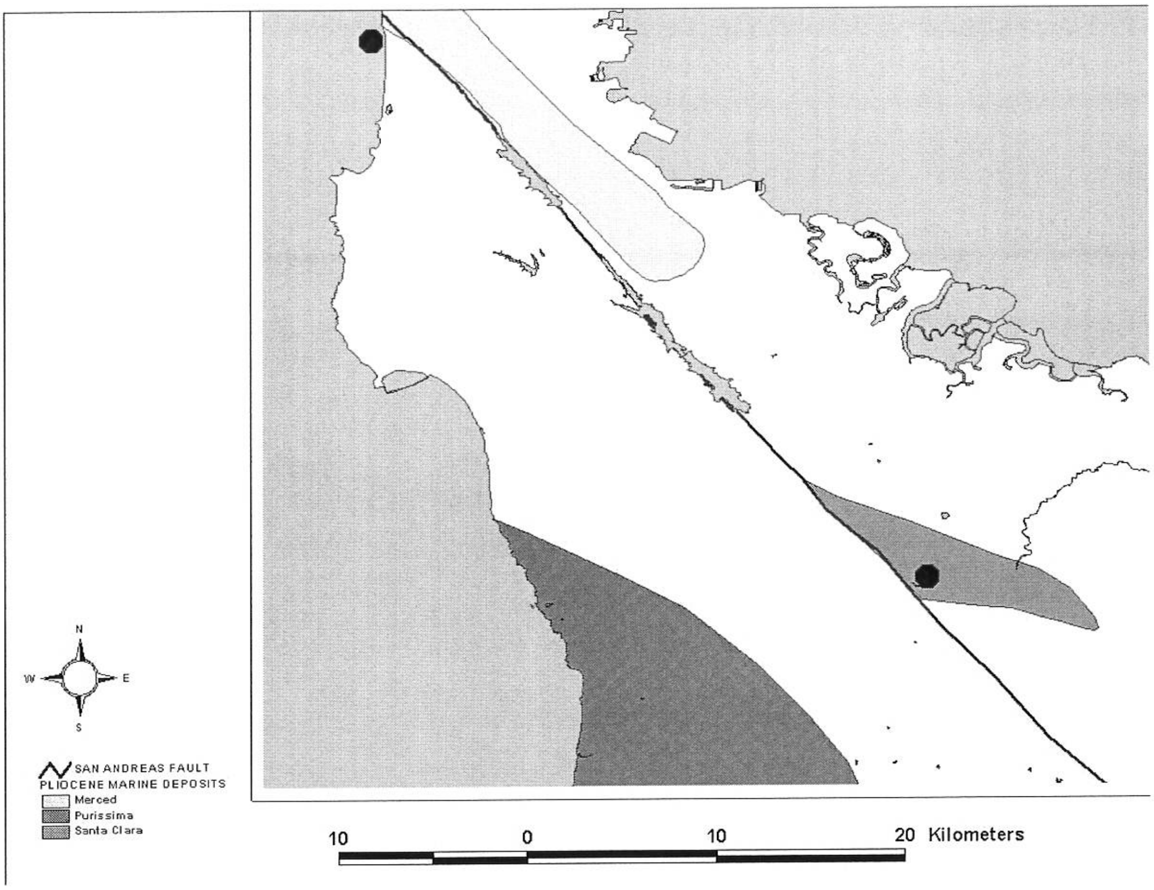


Figure 2.2: *Location of Pliocene marine sediments that have been displaced along the San Andreas fault (adapted from Addicott (1969)). Solid dots indicate equivalent sediments that have been displaced along the San Andreas fault.*

Lawson (1895) was the first to identify the Colma Formation based on an angular unconformity he observed between the base of the formation and the top of the Merced. He described it as consisting of light yellow sands, generally well stratified but poorly consolidated and named it the "Terrace Formations". In his San Francisco Folio (1914) Lawson no longer separated the "Terrace Formations" from the Merced Formation. The first use of the "Colma Formation" was by Schlocker, Bonilla and Radbruch (1958) on the San Francisco North Quadrangle Geologic Map. They named the formation after the town of Colma, which is situated in the center of the area in which the unit is found.

Composition:

The Colma Formation is primarily composed of sand and clay with minor amounts of gravel. Since it is mineralogically similar to the Merced Formation, it is very difficult to draw a line of separation between the two formations at depth. Consequently, it is hard to tell the total thickness of the Colma Formation throughout the whole area where it extends. Therefore, like for the Merced Formation, it is difficult to determine the percentage of each grain size.

Stratigraphy:

In general, the Colma Formation is horizontally stratified and cross-stratified. The stratification is brought out by differences in grain size, differences in color, concentration of heavy minerals, layers of pebbles or zones of scattered pebbles, thin clayey or silty strata, zones of clay fragments, and strata of clay or silty clay ranging in thickness from one centimeter up to a meter or more (Bonilla 1959). In addition, most of the strata are laminated or thin bedded. However, in Westlake one single clay bed attains a thickness of 1.8 meters (Bonilla 1959). Overall, cross-stratification shows considerable variation, i.e. cross-strata range from low angle to high angle, small scale to large scale, and the cross-laminations are either straight or concave upward. The straight cross-laminations range from a high-angle large-scale set of 25 centimeters in thickness to a low-angle large-scale set of 2.5 meters in thickness. Sets of concave upward cross-laminations range in thickness from a few centimeters to 4 meters. Moreover, the dips of the cross-strata at various outcrops in San Francisco and the Westlake District range from 6° up to a maximum of 35° to the northeast (Bonilla 1959, Hochstetler 1973, Schlocker 1974). The steeper dipping laminae are probably dune foreset beds (Bonilla 1971). In Millbrae and Burlingame Pampeyan (1994) observed dips less than 10° to the northeast. At the Sutro Heights exposure the general dips are 20° to 25° SSE, toward Golden Gate Park (Hochstetler 1973).

Age:

The Colma Formation has been dated as Pleistocene in age based on several fossils found throughout the Westside Basin. A *Juniperus californica* trunk recovered near Russian Hill (Schlocker, Bonilla and Radbruch 1958) provided a radiocarbon date of greater than 30,000 years. Savage (1951) found Pleistocene mammalian fossils near Fleishhacker Zoo in San Francisco. Hay (1927) found mammoth bones in San Mateo and Millbrae and assigned them to the Pleistocene. Potbury (1932) determined a Pleistocene age for lignitic seams, logs, cones, and seeds found in a creek bed exposure in the late 1920's close to the current intersection of Jenevein Avenue and Interstate 280, in San Bruno.

Bonilla (1959) deduced that since the Colma Formation is not folded it presumably was deposited after the mid-Pleistocene deformation period; hence, the formation is probably late Pleistocene in age. Kennedy et al. (1982) examined marine invertebrate deposits from the Half Moon Bay terrace deposits and dated them by amino acid racemization methods. They determined the fossils to be 80,000 to 85,000 thousand years. This agrees with Smiths (1960) suggestion that this terrace, which he correlated with the Colma terrace, was cut during the high sea level of the Sangamon Interglacial.

Hochstetler (1973) observed an unconformity in the southern half of the Colma exposure at Fleishhacker Zoo and deduced that the Colma Formation was probably deposited during more than one eustatically high sea level stand. He believed that the most likely time of deposition of the Colma Formation was during the Sangamon and Yarmouth Interglacials.

Clifton et al. (1988) generated a model of Pleistocene global sea levels based on an oxygen-isotope record and concluded that the Colma Formation most likely was deposited during the last interglacial stage, the Sangamon. This agrees with the findings of Hall (1965, 1966) and Hochstetler (1973). The Sangamon corresponds to oxygen-isotopic stage 5, dated at 0.07 to 0.13 million years, or to one of the substages of stage 5 (Shackleton and Opdyke 1973, 1976, Pisias and Moore 1981). This lower age limit is consistent with the upper age limit of the Olema Ash (0.055 to 0.07 million years), which has been found in alluvial deposits correlated with the Colma Formation and unconformably overlie the Merced Formation at the north end of the sea cliff exposures at Fleishhacker Zoo (oral communication by Sarna-Wojcicki to Kennedy and Caskey 2002).

Depositional Environment and Characteristics:

Lawson (1895) assumed that the sands of the Colma Formation were locally derived and mainly represented erosion of the Merced Formation. His assumption was confirmed after Hall (1965) studied the mineralogical composition of the Merced and Colma Formations. Hall (1965) found that the heavy mineral suite of the Colma Formation was very similar to that found in the upper Merced Formation and to the sands currently being carried by the Sacramento River but not to the local Franciscan Group. The Colma Formation as well as the upper part of the Merced Formation show a predominance of hornblende in the heavy mineral suite, which is different from Franciscan suite (Schlocker 1974). In addition, Hochstetler (1973) determined the mean diameter of the Colma sands to be 2.15? and noticed that this value fits well with the mean diameter range determined by Hall (1965) for the upper Merced sands (2.10? to 2.40?). Based on his findings, Schlocker (1974) suggested that uplift and folding of the Merced Formation probably brought the formation above sea level and made it available as a source of the Colma. However, Hochstetler (1973) compared the total volume of the Colma to the total volume of eroded upper Merced (2×10^9 m^3). He deduced that the Sacramento-San Joaquin River system is the source of one quarter of the sands found in the Colma Formation. Sea level was high when the Colma Formation was deposited. Thus, Schlocker (1974) suggested the ancient Sacramento-San Joaquin River system may have provided the silt and clay necessary found in the "Colma estuary". This is how the modern Sacramento-San Joaquin River system supplies sediments to the San Francisco Bay.

Hochstetler (1973) described primary sedimentary structures and textural parameters of several outcrops of the Colma Formation in San Francisco, Daly City and South San Francisco. He concluded that the Colma Formation was deposited in a variety of environments ranging from coastal marine to continental. Sediments of the Colma Formation either accumulated on a broad, gently shoaling coastal margin, or within a broad estuarine system dominated by tidal currents. Inlets and channels of the estuary meandered among resistant knobs of Franciscan rocks, creating an array of islands and quiet water bays. On the margins of these ancient islands marine and continental deposits often interfingered. This allowed colluvium or stream sediments to be deposited in the estuary. Oftentimes, sands were transported landward from the beaches by the prevailing westerly winds, much as they are today, and deposited as coastal dunes. Today Colma dunes can be found at elevations of 140 meters or more and occur alongside stream deposits and colluvium of the Colma Formation (Schlocker 1974). Along the eastern side of the "Colma estuary" Smith (1960) identified a terrace unit at elevations between 60 to 90 meters above sea level and extending for more than 24 kilometers from Colma to Belmont. He correlated this terrace with the Half Moon Bay-Mussel Rock terrace.

Deformation and Faulting:

Uplift and deformation of the Colma Formation can be observed at numerous places. Hochstetler (1973) noticed that these Colma deposits are found at 25 meters above mean sea level (MSL) at Lands End, 16 meters above MSL along the shores of Lake Merced, 80 meters above MSL, at Thornton Beach State Park and 35 meters above MSL near the intersection of Hickey Boulevard and El Camino Real in South San Francisco. Based on these elevations above MSL he concluded that the uplift of the Colma Formation was not uniform throughout its area of deposition. Hochstetler (1973) determined that the amount of uplift is greater adjacent to the San Andreas Rift Zone, suggesting that the deformation is largely a result of movement along the fault. Kennedy and Caskey (2002) pointed out, though, that much of the uplift of the Colma Formation at Thornton Beach is related to the Serra fault. This is also shown in an even more dramatic form on Pampeyan's (1994) geologic map of the Montara Mountain and San Mateo Quadrangles, where in the area from San Bruno to Hillsborough the Colma Formation is overridden along the Serra fault by rocks of the Franciscan Complex and Merced Formation.

2.1.4.3 Old Bay Mud:

Trask and Rolston (1951) first recognized Old Bay Muds and distinguished them from the Young Bay Muds because of their consolidated nature. The thickness of Old Bay Muds varies from 30 meters in the center of the San Francisco Bay to less then 30 cm at the edges of the historical margins of the Bay (Atwater et al. 1977). As shown in

Figure 2.3 Old Bay Muds (Pleistocene Bay Muds) are overlain by Old Alluvium. At places where the Young Alluvium and Old Alluvium are absent, the Old Bay Mud is directly overlain by Young Bay Mud (Schlocker 1974). Oftentimes, bedding in the Old Bay Mud is not apparently visible (Schlocker 1974).

Composition:

Predominantly, the Old Bay Muds consist of clay and silty clay with rare pockets of sand and gravel. The unit is dark greenish gray in color. Once the sediments are exposed they commonly alter to olive gray and dark grayish brown with minor gypsum precipitates. The Old Bay Muds often contain estuarine diatoms, pelecypopds and foraminifera similar to those in Young Bay Muds. Locally, they include peaty clays near contact with older terrestrial deposits (Atwater et al. 1977). Versar EnviroGroup (1996) determined the organic content of the Old Bay Muds collected at 17 meters depth from a well at San Francisco International Airport to be 2 percent, which is lower than that of the Young Bay Mud.

Age:

Atwater et al. (1977) dated the sediments found in boreholes east of the Islais Creek Channel, along the San Mateo Bridge and along the Dumbarton Bridge. They assigned the Old Bay Mud to the Sangamon noting that the sediments from the base of the Old Bay Muds are about 100,000 years and that the disconformably overlying terrestrial deposits are 40,000 years old. Consequently, the Old Bay Mud has the same age as the Colma Formation (70,000 to 130,000 years). In fact, the Old Bay Mud is probably the estuarine facies of the Colma Formation. This hypothesis agrees with Hochstetler's (1973) palinstatic map of the San Francisco Peninsula. The map illustrates how the deposition of the Colma Formation occurred.

Depositional Environment:

Old Bay Muds are composed of the finest grained sediment carried by creeks that ran into the ancient San Francisco Bay as well as by the ancient Sacramento River. The mud was moved around the San Francisco Bay by tidal currents and waves. In addition, they were deposited primarily in brackish to salt water marshes between mean sea level and high tide line (Helley et al. 1979). After the end of the Sangamon the Old Bay Muds were exposed at the Wisconsin on land surface where sustained oxidation, desiccation, leaching of calcareous fossils, and penetration by roots to a depth of several meters occurred (Atwater et al. 1977).

Tectonic Activity:

Atwater et al. (1977) concluded that the San Francisco Bay has been subsiding over the last 300,000 years but at different rates. They determined that the deepest Sangamon estuarine deposits subsided tectonically 20-40 meters in about 100,000 years (0.2±0.1 to 0.4±0.1 mm/year) (Atwater et al. 1977).

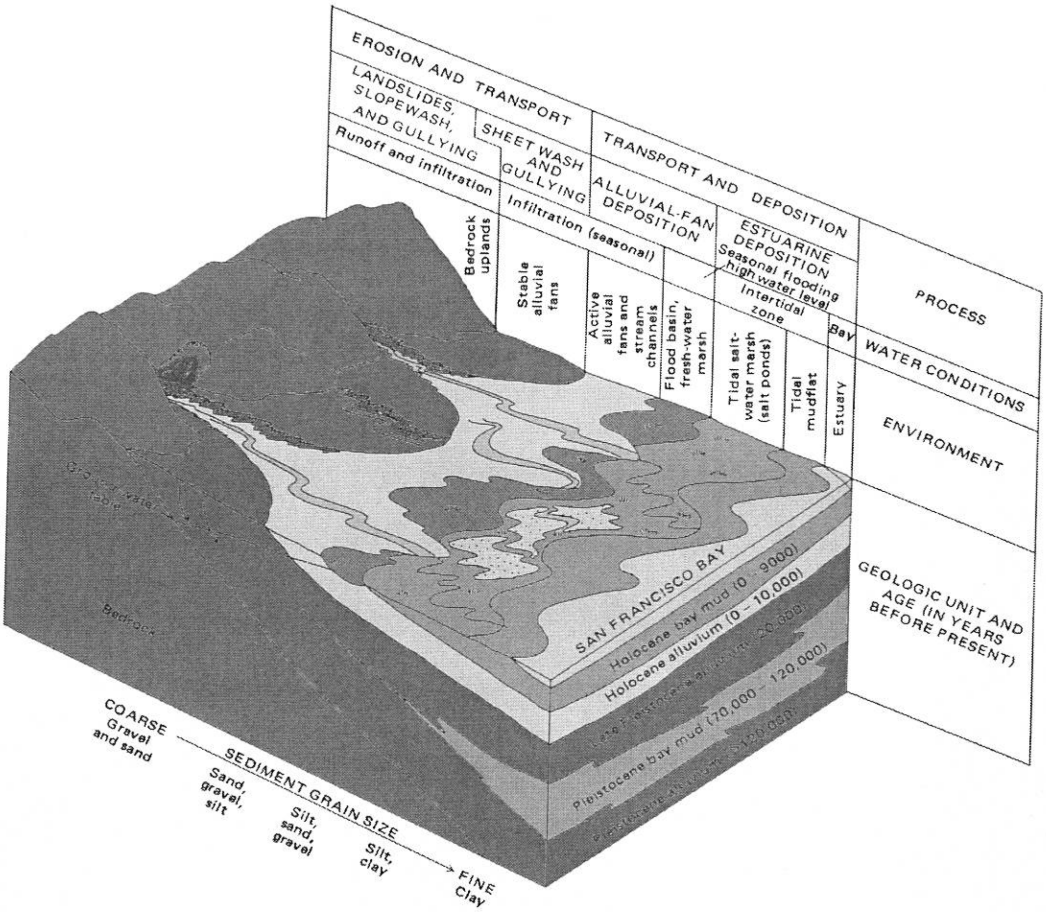


Figure 2.3: *Conceptual model of the stratigraphy along much of the San Francisco Bay showing modern depositional and erosional processes. The thickness of the various sedimentary deposits varies locally. The diagram was adapted from Helley et al. (1979).*

2.1.5 Holocene Deposits

2.1.5.1 Young Bay Muds

Between 1853 to 1869 the US Coast Survey produced topographic maps that show the historic landward extent of the margins of the San Francisco Peninsula. These maps indicate the area of occurrence of Young Bay Muds (Figure 2.4). Over the last 125 years, much of the Young Bay Mud has been covered by artificial fill changing the coastline around the San Francisco Bay. The thickness of the Young Bay Muds is as much as 37 meters beneath San Francisco Bay and thins to less than 30 centimeters around the margins of the Bay (Helley et al., 1979).

As shown in Figure 2.3, Young Bay Muds generally overlay young (Holocene) alluvial deposits and Old Alluvium and interfinger with young alluvial deposits along the margins of the San Francisco Bay. They form flat marshlands with low levees adjacent to tidal sloughs and gently sloping mudflats exposed only during low tides (Helley et al. 1979). At places, the young alluvium is absent and Young Bay Mud directly overlies Old Bay Mud (Schlocker 1974). Bedding is not readily apparent in some mud and clay, but in others it is shown by sand partings, 1-3 mm thick, separating clay layers 0.5 to 20 cm thick (Schlocker 1974).

Composition:

Young Bay Muds are composed of clay and silty clay that are rich in organic material. On average, clays make 50% of the sediment composition (Versar-EnviroGroup (1996), but they can range from 30-60% (Schlocker 1974). Silt makes up 30-65% of the sediment grains and sand 1-10%. In their natural state, the Young Bay Muds are generally olive gray to dark gray. However, when dried, the color lightens typically to greenish gray or light olive gray (Schlocker 1974). Locally, lenses and stringers of well-sorted silt and sand (1 cm to several meters thick), beds of peat and fresh and brackish water gastropod and pelecypod shells are found within the unit (Helley et al. 1979, Schlocker 1974).

Mineralogically, Young Bay Muds are composed mostly of montmorillonite. Samples collected and analyzed by Schlocker (1974) from the east shore of San Francisco and from Richardson Bay showed a content of 50-60% montmorillonite, 20-30% mica and 10-20% chlorite. The sand grains were mostly composed of quartz and plagioclase feldspar with minor amounts of potassium feldspar, rock and shell fragments.

Age:

Young Bay Muds are being reworked and deposited by current geologic processes. Their age represents a time span since the last interglacial period when sea level rose and entered the San Francisco Bay. The oldest basal deposits of the Young Bay Muds are, thus, found closer to the Golden Gate, while the youngest basal deposits are found at the edges of San Francisco Bay (Figure 2.4). Atwater et al. (1977) and Helley et al. (1979) determined the maximum age of Young Bay Mud by recording changes in sea level within San Francisco Bay. They used radiocarbon ages for tidal marsh deposits located at the base of Holocene estuarine sediments to date Young Bay Mud. Marsh sediments accumulated when sea levels were lower than today. According to their findings, Atwater et al. (1977) and Helley et al. (1979) believed the rising sea entered the Golden Gate 10,000-11,000 years ago and moved land inward at about 30 meters per year. The rising sea level reached the Dumbarton Bridge about

8,000 years ago. Subsequent shoreline changes have been more gradual because of a decrease in the rate of sea level rise since about 5,000-6,000 years ago (Helley et al. 1979). In fact, the oldest dated deposits in the San Francisco Bay basin are 9,600 years old (Atwater et al. 1977). Thus, Young Bay Muds accumulated during the last 125 years can be separated from their older underlying counterparts based on their molluscan fauna. They contain non-native species, which have been introduced into San Francisco Bay in the last 125 years (Helley et al. 1979).

Depositional Environment:

Young Bay Mud is composed of fine grained sediment carried by creeks that run into San Francisco Bay as well as by the Sacramento River; they are reworked by tidal currents and waves. The mud was deposited primarily in brackish to salt water marshes between mean sea level and high tide line (2.5 meters) (Helley et al. 1979).

Tectonic Activity:

Atwater et al. (1977) concluded that San Francisco Bay has been subsiding over the last 300,000 years but at different rates. They observed that 6,000 years old salt marsh deposits found in the lower part of the Young Bay Muds had subsided 5 meters. Based on this observation they determined a subsidence rate of the bay of about 0.8 ± 0.7 mm/yr for the last 6,000 years.

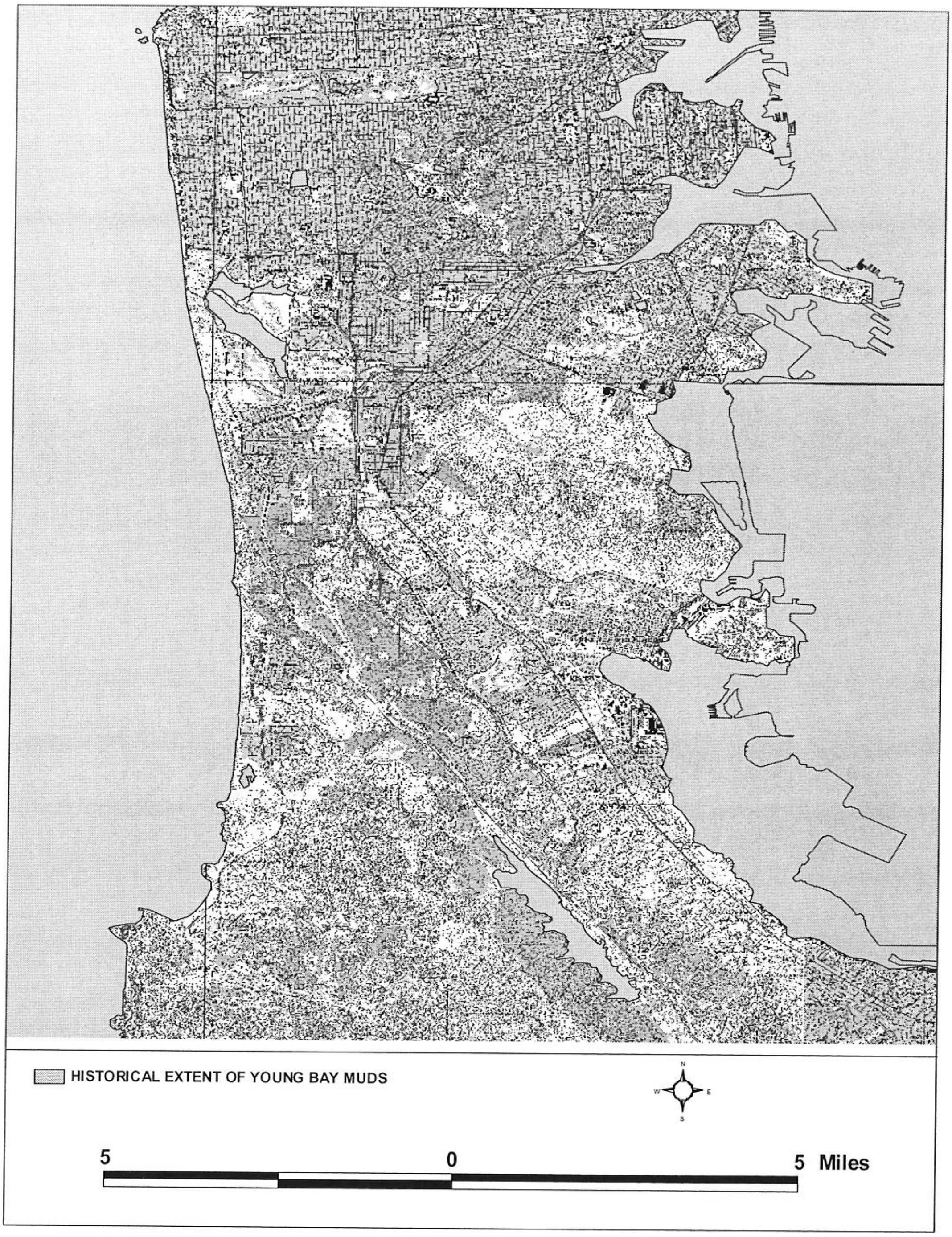


Figure 2.4: *Distribution of the Young Bay Mud based on the historical shoreline mapped by the US Coast Survey (1853, 1854, 1857a, 1857b, 1867, 1868, 1869). The area between the historic and the current shoreline is now covered with artificial fill. The map was adapted from Helley et al. (1979).*

2.1.5.2 Sand Dunes

Coastal dune sands overly the Colma Formation over most of the west side of San Francisco north of Lake Merced, extending inland to Twin Peaks in the east (Figure 1.2). Historical maps and photographs indicate that active dunes were widespread prior to urbanization (Schlocker 1974, Olmsted and Olmsted 1979). Active dunes that existed west of Sunset Boulevard and south of Ortega Street were of the transverse-ridge type (Schlocker 1974). Most of the dunes are now covered with buildings, except along the beach where few rare dunes exist near Fleishhacker Zoo. Vague outlines of old sand dunes can be found at Golden Gate Park. In general, the thickness of the sand dunes ranges from 0 to 45 meters (Schlocker 1974). However, at the Golden Gate Park their thickness ranges from 0 to 24 (Schlocker 1974) meters whereas near Lake Merced they range from 0 to 15 meters (Yates et al. 1990).

Sand dunes unconformably overly the Colma and Merced Formations. The unconformity can be observed at Fleishhacker Zoo but a distinct separation of the sand dunes from the Colma Formation in borings is very difficult. Hochstetler (1973) observed that sand dunes generally show steeply dipping, large-scale cross bedding, which concaves upward. Trough cross bedding is rare.

Composition:

Sand dunes consist of loose, clean, well-sorted, fine- to medium-grain, gray sands of varying lithology (Phillips et al. 1993). No detrital clays or silts are present and pebbles occur rarely (Hochstetler 1973). An increase in sorting and roundness of the sand can be observed from west to east across San Francisco. Schlocker (1974) determined that the mean diameter for modern dune sands in San Francisco ranges from 0.192mm (2.38?) to 0.266 mm (1.91?). Most sand grains are subrounded or subangular, and polished. Quartz, feldspar, and chert make up 70 to 85% of the dune sand (Kirker, Chapman and Associates 1972). The heavy mineral composition of the dune sands consists of hornblende, pyroxene, clino-zoisite-epidote, hypersthene, zircon, magnetite, ilmenite, chromite, sphene, monazite, and apatite (Schlocker 1974).

Age and Depositional Environment:

Sand dunes have been formed since sometime during the last glacial period. As in the case of the upper Merced and Colma formations, the main source of sediment for the sand dunes was derived from the Sacramento River. During the last glacial period sediments transported by the Sacramento River were deposited outside the Golden Gate. Long shore drift redeposited the sand at the beaches and wind transported it from there inland onto the plain west of the gate. With the end of the last glacial period the Sacramento River no longer deposited the majority of its sediments outside the Golden Gate; thus the main source of sand since then has come from the Merced and Colma formations, which are exposed along the coastal bluffs south of Fleishhacker Zoo (Schlocker 1974). Sand located there has been transported along the coast and has been deposited at Ocean Beach. From this location wind has transported the sand from Ocean Beach inland to the east into the Sunset and Richmond districts. Sand dunes in those areas were active until about the 1950's when urban development started (Schlocker 1974). In fact, there are still active sand dunes still can be found at Fort Funston.

2.1.5.3 Alluvial Deposits

As shown in Figure 2.3 the alluvial deposits on the San Francisco Peninsula can be subdivided into Old Alluvium of Pleistocene age and Young Alluvium of Holocene age (Atwater et al. 1977, Helley et al. 1979). Bonilla (1959) already tried separating both units in the Westlake District of Daly City but mentioned that in places the subdivision is not feasible. In this thesis both alluvia will be discussed separately in accordance to Bonilla's (1959) nomenclature.

OLD ALLUVIUM:

Old Alluvium forms terraces in larger canyons in Daly City and northeastern and southwestern flanks of Buri-Buri valley. These terraces thin rapidly toward the valley walls, but in the heads of the canyons the alluvium covers broad areas that extend well up into the highlands. The average thickness of older alluvium is about 7.5 meters, but in places it can reach 14 meters. Most of the older alluvium is medium gray in color, but ranges from light gray to dark gray and in a few places it is yellowish-orange (Bonilla 1959).

Composition and Structure:

In its lower part the Old Alluvium is sandy and has a few beds of gravel. However, in its upper part it tends to be silty. Close to the surface the Old Alluvium is a compact clayey silty sand or clayey sandy silt, medium gray or dark gray in color, containing scattered pebbles and, in places, fragments of wood and other organic matter (Bonilla 1959).

Stratification is generally not visible in Old Alluvium, but where discernable it is brought out by differences in resistance to erosion, by color banding, or by lines of pebbles. The crude stratification that is visible in places has a low dip, usually 10° or less.

Age and Depositional Environment:

Bonilla (1959) assigned Old Alluvium to the late Pleistocene. Additionally, Atwater et al (1977) dated Old Alluvium, which was deposited over the Old Bay Muds to be 40,000 years old. Helley et al. (1979) assigned an average age of 20,000 years to the Old Alluvium. These ages are younger than those of the Colma Formation but, in part younger than those of sand dunes. Therefore, locally in San Francisco, sand dunes might be overlying Old Alluvium.

YOUNG ALLUVIUM:

Small thin surficial deposits of Young Alluvium occur at scattered locations throughout the San Francisco Peninsula. The deposits tend to be long and narrow along streams or triangular behind artificial barriers such as railroad and highway fills and debris dams (Bonilla 1959, Kirker, Chapman and Associates 1972). In places the alluvium behind artificial barriers contain layers of artificial fill. Bonilla (1959) observed a 30 meters composite deposit behind an artificial fill on the old, abandoned coast highway. However, the Young Alluvium along the streams is seldom more than a meter thick.

Composition:

The Young Alluvium is derived primarily from the Merced and Colma Formations and consequently it consists mostly of poorly sorted sand, silt and clay with an estimated porosity of 35% (Bonilla 1959, Kirker, Chapman and Associates 1972).

Age and Depositional Environment:

As sea level rose throughout the Holocene the base level of the streams in the San Francisco Bay region were raised slightly; consequently, Young Alluvial sediments were deposited on flood plains around the growing bay (Helley et al. 1979). At bay margins, the Young Alluvium interfingers with the Young Bay Mud. Urbanization in the San

Francisco Bay Area has altered drainage channels in the basin, thereby, eliminating the accumulation of younger alluvium (Pampeyan 1994).

2.2 Tectonics:

2.2.1 San Andreas Fault

The San Andreas fault is one of four major structural boundaries in California separating the granitic-metamorphic complex from the Franciscan Complex (Page 1966), in particular, the Salinian Block to the west and the Franciscan Complex to the east (Reed 1933). It marks the boundary between the North American and Pacific Plates (Pampeyan 1994). In general, the area west of the fault has been displaced northwestward by at least 420 km (Page 1966) at an average rate of 3.51 to 5 cm per year (Bonilla 1959, Argus and Gordon 1990). The fault was formally named by Lawson (1908) after the San Andreas Valley west of Millbrae.

The San Andreas fault enters the coast on the San Francisco Peninsula about 0.6 km north of Mussel Rock and trends inland southeastward from there (Bonilla, 1959). The San Andreas fault follows Skyline Boulevard between Daly City and Pacifica and in northwestern San Bruno. The fault is obvious for a stretch of 14.5 km parallel to Highway 280 between San Bruno Avenue and the interchange with Highway 92, where it crosses the length of San Andreas Lake in the north and Crystal Springs Reservoir in the south.

On the San Francisco Peninsula, the San Andreas fault builds an exception to this generalized boundary concept. It is a zone of faulting with a maximum width of about 150 meters (Pampeyan 1994) running entirely through Franciscan Complex from Woodside, through Mussel Rock, to an unspecified point off the Golden Gate. The Pilarcitos fault, probably an ancestral strand of the San Andreas fault (Wakabayashi 1996b), forms the basement boundary north of Woodside (Pampeyan 1994). The total dextral movement between plate boundaries in the Bay Area is not solely accommodated on the San Andreas fault (Prescott et. al. 1981, Lisowski and Savage 1992, Page 1992). Movement is distributed along several parallel faults such as the San Gregorio, the Hayward-Rodgers Creek, the Calaveras-Concord-Green Valley and the Greenville faults (Page 1992, Hall et al. 1999). Sedlock (1995), Wakabayashi and Hengesh (1995) as well as Wakabayashi (1999b) concluded that the total offset on the peninsular segment of the San Andreas fault is between 22 and 27 km. Based on studies conducted by WGCEP (1990), Hall (1984), Cummings (1983), Addicott (1969) and Weber and Cotton (1981) the estimated average slip rate on the peninsular segment of the San Andreas fault is 19 ± 4 mm per year. More recently, Hall et al. (1999) proposed a horizontal slip rate of 17 ± 4 mm a year based on a paleoseismic investigation of the San Andreas fault at the Filoli Center, north of Woodside. They also looked into the vertical component of displacement on the San Andreas fault on the San Francisco Peninsula and concluded that the average vertical slip rate over the last about 2,000 years is about 1 ± 0.2 mm per year, west side up. The ratio of horizontal to vertical slip at the Filoli site is thus about 17:1 for the late Holocene (Hall et al. 1999).

Another major component of the San Andreas fault is contraction normal to the fault. This can be noticed by the presence of large-amplitude folds and related thrust faults (such as Serra, Belmont, Atherton, Pulgas and Monte Vista faults) that deform Pliocene and younger rocks throughout the central Coast Ranges along the San Andreas fault (Jones 1992, Sedlock 1995). Each major splay of the San Andreas fault System has an attendant parallel thrust belt that roots within the strike-slip fault zone and dips either to the east or west (Jones 1992). West verging thrusts are blind; east-verging thrusts break through the surface and define pop-up blocks. Vergence of these subsidiary thrust belts, viewed as long-term strain indicators, suggest that the San Andreas fault north of Gilroy dips to the west (Jones 1992). The Loma Prieta Domain (Figure 2.5) was the name given by Sedlock (1995) to the area of thrust faults west of the San Andreas fault on the San Francisco Peninsula.

Section 2.2.2 The San Bruno Fault

The San Bruno fault extends northwestward from San Francisco Bay, along the southwest side of San Bruno Mountains and passes through the Lake Merced area. Its age, exact location, and offset are uncertain, since the fault is concealed by the Colma Formation (Bonilla 1959, Yates et al. 1990, Applied Consultants 1991, Phillips et al. 1993). Lawson (1895) originally proposed the San Bruno fault to explain the absence of outcrops of the Merced Formation along the flanks of Mount Davidson and San Bruno Mountains. He estimated the vertical offset of the San Bruno fault to be at least 2,100 meters. By reanalyzing the location of the San Bruno fault using a bedrock contour map

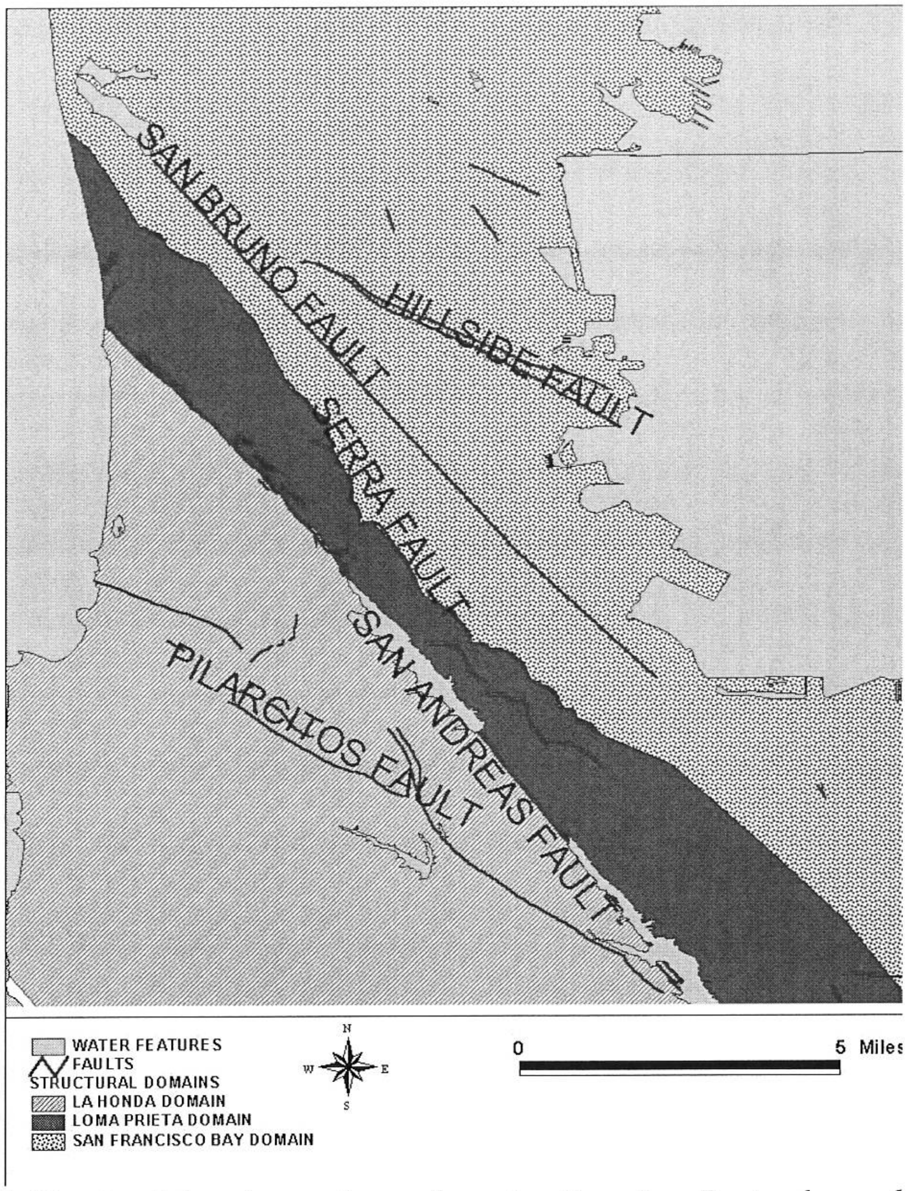


Figure 2.5: *Structural domains on the northern San Francisco Peninsula; modified after Sedlock (1995).*

generated for the San Francisco South 7 ½ Minutes Quadrangle, Bonilla (1964, 1971) determined the fault lies approximately along the axis of the south arm of Lake Merced. He determined that the vertical offset is about 520 meters in the vicinity of Lake Merced. Based on onshore seismic reflection profiles between Fleishhacker Zoo and Stern Grove, Caldwell-Gonzalez-Kennedy-Tudor (1982) reportedly showed no fault at that location proposed by Bonilla (1964), but indicated a fault 460 meters farther east with a vertical offset of about 60 meters, which they assumed to be the San Bruno Fault. Furthermore, Yates et al. (1990) pointed out that linear features in offshore seismic reflection data could align with both Bonilla's (1964) and Caldwell-Gonzalez-Kennedy-Tudor's (1982) onshore location for the San Bruno fault.

The amount of seismic activity on the San Bruno fault is another uncertain. Although Lawson (1895) and Bonilla (1971) considered the fault inactive, Brabb and Hanna (1979) reported microseismic activity along a line that could be the offshore extension of the San Bruno fault. They stated, that the seismic activity could also be related to movement along the nearby San Andreas fault. Wakabayashi (1999) considers the San Bruno fault dormant. He stated that major activity on this fault occurred in the time period from 15 to 18 million years ago with displacement ranging from 30 to 50 km (Wakabayashi 1999). Interestingly, from 0.2 to 2 million years ago the northern segment of the San Bruno fault changed its activity role and accommodated movement as a pull-apart boundary fault (written communication by Wakabayashi 1998).

Despite all aforementioned considerations, the U.S. Geological Survey (1997) and Bonilla et al. (2000) raised serious doubts about the existence of the San Bruno fault after a detailed fault investigation including geomorphic, geologic and geophysical analyses to look for normal or strike-slip fault displacement. The results of each analysis did not provide any compelling evidence supporting the existence of the San Bruno fault.

The existence or not of the San Bruno fault has considerable implication on the stratigraphy and hydrogeology of the Westside Basin. If the fault exists and it extends through the Merced Formation, then clay layers that have been identified in boreholes under Lake Merced (Caldwell-Gonzalez-Kennedy-Tudor's (1982), Yates et al. (1990)) would be offset, which could create a barrier to horizontal groundwater flow (Yates et al. 1990). However, since the current understanding seems to indicate that the fault does not exist the San Bruno fault will be disregarded in the further course of this thesis.

2.2.3 The Serra Fault

The Serra fault is a series of thrust faults parallel to the San Andreas fault in the Coast Ranges. The presence of thrust faults on the northeast side of the San Andreas fault is very common (Page 1966, Jones 1992) and is a result of contraction normal to the San Andreas fault (Page 1992). Other faults similar in behavior on the San Francisco Peninsula are Belmont, Atherton, Pulgas and Monte Vista faults. Willis (1938) considered all of these faults to be one, called them the Foothills Thrust fault, and produced a map with approximate location of the fault. Later, more detailed mapping of the San Francisco Peninsula pinpointed the location of each specific thrust fault. Sedlock (1995) referred to this area of thrust faults east of the San Andreas fault on the San Francisco Peninsula as the Loma Prieta Domain (Figure 2.5).

Most of these thrust faults are steep (Page 1966), rooted within the strike slip zone of the San Andreas fault (Jones 1992) and show dip separations in the northeast-southwest direction on the order of 300 to 3000 meters (Page 1966). These thrust faults deform or even override Pliocene and younger rocks (Bailey et al. 1964, Jones 1992, Sedlock 1995), producing parallel, large-amplitude folds (Page 1966) and often break through the surface, creating pop-up blocks (Jones, 1992). It is important to note that all of these faults have been active during the Quaternary (Page 1966).

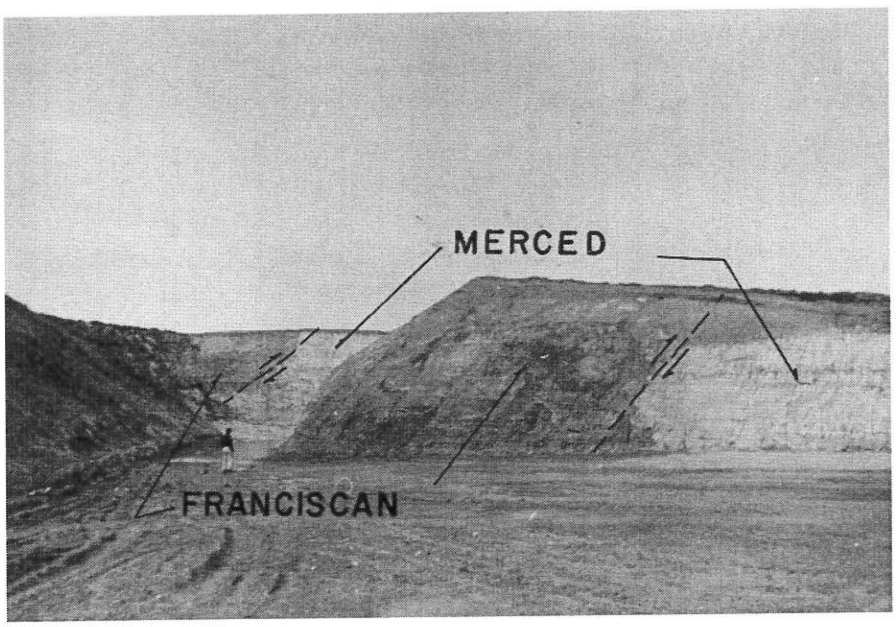


Figure 2.6: *Pop-up block of Franciscan Complex and Merced Formation between strands of the Serra fault. The outcrop was generated during grading operations in west Millbrae. Photo taken by Smith (1960).*

As for the Serra fault, it extends from Hillsborough in the south (Pampeyan 1994) to Fort Funston in the north (Kennedy and Caskey 2002). It was first noted in 1955 in the Montara Mountain Quadrangle by Bonilla and about 1957 named on his geologic map of the San Francisco South Quadrangle (1965, 1971). Bonilla and Appledorn (1955) examined and photographed an artificial exposure about half a mile east of Crestmoor

High School, at the east edge of Junipero Serra County Park. They determined that one of the shallow west-dipping faults exposed there displaced beds of the Merced Formation, and modern soil (Pampeyan 1994). Smith (1960) photographed a few strands of the fault (Figure 2.6), which were exposed during grading operations in west Millbrae, and plotted their position on his map.

The extent and amount of thrusting and deformation along the Serra fault decreases from south to north. Between Hillsborough and Millbrae the Serra faults occurs as imbricated strands juxtaposing Franciscan and Merced rocks in zones at least 900 meters wide (Pampeyan 1994). In San Bruno, the Serra fault dips 20°-40° west and places Franciscan sheared rock on top of the Colma Formation (Pampeyan 1994). Pampeyan (1994) determined this angle based on poor exposures of the mélange in the Buri-Buri Ridge, which plot as curvilinear boundaries. Bonilla (1965, 1971, 1994, 1998) mapped the Serra fault as breaking through the surface as far north as Fleetwood Drive, in San Bruno, and with fault dips ranging from 20° to 60°. He also shows several synclinal and anticlinal axes that parallel both the San Andreas and the Serra faults in the Westborough District and in Daly City. One of these anticlines falls in line with the location of the Wood's Gulch fault as mapped by Ashley (1895) and GEO Consultants (1998). A second anticline also falls in line with a fault mapped by Eagle and Squire (1974) cutting diagonally across the face of the Thornton Bluffs, about 1/3 of the way down from the Lynvale Court cul-de-sac. Brabb and Olson (1986) mapped the Serra fault as far north as Broadmoore, where Merced Formation is placed on top of Colma Formation. The location of this stretch of the Serra fault also agrees with aeromagnetic data by Bonilla et al. (2000). Barr (1999) identified the Serra fault as a blind fault crossing the Olympic Country Club based on an outcrop of the Rockland Ash found in sequence S of the Merced Formation and an east-vergent fold of the Merced Formation with the eastern limb dipping 80°. Kennedy and Caskey (2002) inferred the trace of the blind Serra fault as going through sequence U of the Merced Formation along the coastal bluffs at Fort Funston. There, the forelimb of the east-vergent fold of the Merced dips 65° to the northeast.

Aside from the mainly vertical movement of the Serra fault, Hengesh et al. (1996) also suggested small right-lateral component of slip occurring on the fault, thus, accommodating a component of San Andreas fault motion. Their findings are based on slickensides they found in a trench exposure of the Serra fault.

2.2.4 Other Faults

The Hillside Fault:

The Hillside fault trends southeast northwest along the southwest side of the San Bruno Mountains from Oyster Point till the south end of Lake Merced. Crandall (1907) first mapped the Hillside fault and identified it as a thrust fault with an upthrow of up to 450 meters, but, erroneously, considered it to be Lawson's (1895) San Bruno fault. Lawson (1908) considered the Hillside fault to be an auxiliary fault of the San Bruno fault. Bonilla (1959) first named the Hillside fault and identified it as an independent feature.

The Hillside fault runs through the Franciscan Complex and, where exposed, it can be identified along a line of sheared rocks, serpentinite, and other metamorphic rocks (Bonilla 1959). The fault is mostly covered by the Colma Formation and younger deposits at Oyster Point and by the Merced and Colma formations northwest of the San Bruno Mountains. Based on aeromagnetic data Bonilla et al. (2000) identified the extension of the Hillside fault under the Merced Formation as far to the northwest as the southern end of Lake Merced.

The Wood's Gulch Fault:

The Wood's Gulch fault runs southeast northwest along the main axis of Wood's Gulch and is in line with an anticline mapped by Bonilla (1998) in the Westlake District of Daly City. It was first identified by Ashley (1895) who assigned 250 meters of vertical offset along the fault. Bonilla (1959) did not support the existence of the fault as described by Ashley (1895) and pointed out that the inland trace of the fault is actually the main drainage of Colma Creek. GEI Consultants (1998) mapped two traces of the fault exposed by erosion and landsliding in the gulch and named them the north and south trace of the Wood's Gulch fault. According to their findings, the two traces separate three areas of significantly different dip and two zones of predominantly different lithologies. Although the total amount of offset is unknown at Wood's Gulch, Clifton and Hunter (1987) point out that due to the stratigraphic relationship between sequences B and C and the succession of sequences ZZ-A-B-C and C-D-E-F of the Merced Formation no significant faulting occurs in the area.

The City College Shear Zone:

The City College shear zone occupies a band about 0.8 to 1.6 km wide extending from Lincoln Park southeastward to San Francisco Bay near Bayshore. It crosses Golden Gate Park about 1.6 km from the coast, between the Elk Glenn Lake and the Golden Gate Park Stadium and extends southeastwards across the eastern end of Stern Grove. The shear zone contains intensely sheared cataclasite and blocks up to 60 meters in diameter (Dames and Moore, 1979). The City College Shear Zone appears to affect only bedrock and separates the Marin Headlands terrane on the northeast side from the San Bruno Mountains terrane on the southwest (Wakabayashi 1999). Geologic sections and bedrock contour maps prepared by previous investigators have not indicated any vertical offset in the bedrock surface near the fault zone (Bonilla 1971, Schlocker 1974, Dames and Moore 1979, Caldwell-Gonzalez-Kennedy-Tudor 1982, Yates et al. 1990).

Unnamed fault at Lynvale Court:

Eagle and Squire (1974) mapped a fault cutting diagonally across the face of the Thornton Bluffs, about 1/3 of the way down from the Lynvale Court cul-de-sac. This fault falls in line with an anticline mapped by Bonilla (1998) in the Westlake District of

Daly City. The surface expression of this fault suggests that movement has occurred in the very recent geologic past; evidence for this displacement is a furrow associated with its surface trace that can be traced uninterrupted through the southern end of Thornton Bluffs landslide (Eagle and Squires 1974).

Chapter 3

HYDROGEOLOGIC SETTING

3.1 Conceptual Model and Basin Boundaries

3.1.1 Introduction:

The Westside Basin has many different water bearing zones. Despite the fact that (i) different studies (Kirker, Chapman and Associates 1972, Boone, Cook and Associates 1987, Yates et al. 1990, Phillips et al. 1993, San Mateo County Environmental Health 2001a, 2001b, 2001c, 2002a) indicate differences in water level and water quality throughout of the basin, and (ii) that some of these water-bearing units provide drinking water for Daly City, South San Francisco and San Bruno, there hasn't been a clear differentiation between the different water bearing zones. In addition, shallow aquifers are known to the County of San Mateo to be polluted by a wide range of contaminants. Accordingly, in this chapter a hydrogeologic assessment of the basin is presented.

Assemblage and comparison of stratigraphic data and characteristics (discussed in Chapter 2), water quality (discussed in section 3.2) and water age dating techniques (discussed in chapter 4) are useful tools to delineating different water-bearing zones. They allow the identification of hydrostratigraphic units and their interconnectivity. In this section I will summarize the results from previous hydrogeologic investigations conducted in the Westside Basin as well as discuss recently collected water level and water quality data. The discussion of this data supports the conceptual model presented in the subsequent section.

3.1.2 Conceptual Model:

The Westside Basin is composed of different unconsolidated geologic units, which comprise the various hydrostratigraphic units of the basin. Conceptually, the basement of the basin is defined by the Franciscan Group (Figure 3.1). The Franciscan Group is also found along the northern, northeastern and southwestern fringes of the Westside Basin. Although the Franciscan Group has a much lower hydraulic conductivity than the overlying unconsolidated sediments, locally, groundwater flow from the Franciscan Group to the overlying unconsolidated sediments does occur.

As shown in Figure 3.1, groundwater flow in the basin is not only controlled by lithology but also by the tectonic setting of the Basin. West of the Serra fault groundwater flow is towards the Pacific Ocean (Fio, oral communication April 2003). East of the Serra fault groundwater flow regime is towards the center of the Buri-Buri Valley and from the valley center to the southeast. The valley axes runs northwest-southeast and crosses Lake Merced. Therefore, north of Lake Merced groundwater flow is towards the Pacific Ocean. South of Lake Merced groundwater flows along the main axis of the valley from Daly City to San Bruno. Furthermore, there is a small vertical component to groundwater movement from the upper hydrostratigraphic units to the lower ones. However, as isotopic data indicates (see section 3.3.3), this movement slow, mostly retarded by the presence of different aquitards.

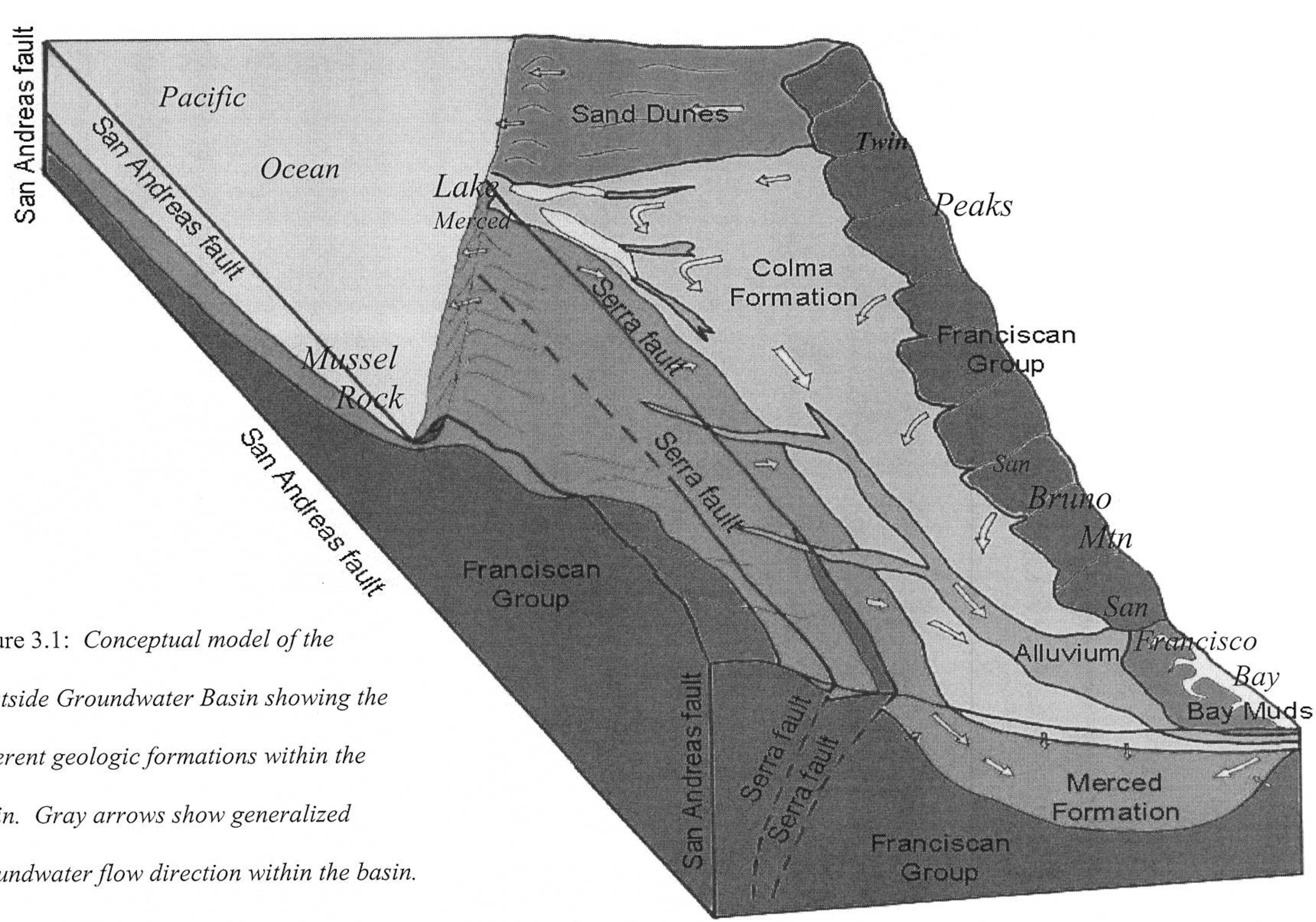


Figure 3.1: *Conceptual model of the Westside Groundwater Basin showing the different geologic formations within the basin. Gray arrows show generalized groundwater flow direction within the basin.*

3.1.3 Horizontal Basin Boundaries:

The first attempt to assign boundaries to the Westside Basin was done by Phillips et al. (1993). Their research utilized previous studies (Kirker, Chapman and Associates (1972), Boone Cooks and Associates (1987), Yates et al. (1990) and Applied Consultants (1991)) to delineate horizontal boundaries. For example, the northern boundary was defined by a subsurface bedrock rise in the eastern part of Golden Gate Park and the Richmond District. To the northeast and east from San Francisco to South San Francisco bedrock outcrops of Mount Davidson, San Bruno Mountain and Oyster Point act as basin a boundary.

From South San Francisco to the south the basin is open to the east and extents to an unknown distance under San Francisco Bay. The areal extent of the southern boundary has yet to be accurately defined. However, Applied Consultants (1991) recognized that the Merced and Colma formations extend as far south as Burlingame, but they assigned the southernmost extent of the Westside Basin further north, to San Bruno. Whereas, Phillips et al. (1993) argued that the southern boundary should be further south, just south of the airport and running through Millbrae. His determination is based on higher clay contents found in the Merced Formation from Millbrae southward. This boundary has since been accepted, for lack of better understanding, by subsequent studies as a possible southern boundary (CH2MHill (1994, 1996, 1997), Luhdorff and Scalmanini (2002)) for the groundwater basin. Further discussion on the southern boundary of the Westside Basin is presented in Chapter 4.

To the southeast the San Andreas fault has been recognized as a basin boundary (Phillips et al. 1993), since, (i) the Merced Formation does, except for a small area at Mussel Rock, not extend beyond the San Andreas fault, and (ii) fault gouge would inhibit horizontal groundwater flow across the fault.

The Westside Basin extends to the west an unknown distance offshore under the Pacific Ocean (Figure 3.1). There, like on the San Francisco Peninsula, the San Andreas fault might also be the basin boundary.

3.1.4 Vertical Basin Boundaries:

(I) Basement:

Bedrock from the Franciscan Complex has been proposed to be the base of the Westside Basin (Yates et al. 1990). Their determination is made on the low hydraulic conductivity of bedrock compared with the overlying unconsolidated sedimentary deposits.

Caldwell-Gonzalez-Kennedy-Tudor (1982) and Burns and McDonnell (2002) showed that groundwater flow in the Franciscan Complex does occur. Most of this groundwater flow is in form of fracture flow and contributes small amounts of groundwater to the overlying sediments by means of "buried springs". The behavior of these springs as similar to above surface springs that can be observed at bedrock outcrops in San Francisco. Nevertheless, as stated by Yates et al. (1990), the total amount of fracture flow can be considered minimal and, therefore, the Franciscan Complex can be regarded as the basement of the groundwater basin.

Due to the above-mentioned hydrogeologic character of the Franciscan Complex it is fundamental to the study to look for the bedrock surface in order to identify the total thickness of the groundwater basin. One main characteristic of the bedrock surface is that it is highly uneven. In San Francisco, from Golden Gate Park to Lake Merced, borehole data suggests steep slopes in the buried bedrock, just as those observed on the slopes of Mount Davidson and possibly, locally, even the presence of buried canyons (Harding Lawson Associates 1976a, Caldwell-Gonzalez-Kennedy-Tudor 1982, Yates et al. 1990). In San Mateo County, borehole information, as well as, geophysical evidence indicates the presence of a deep buried southeast-northwest trending canyon with its deepest part along the coastal bluffs in Daly City (about 1,000 meters deep) and shallowing up to the southeast (less than 10 meters in Burlingame) (Bonilla 1971, Bonilla et al. 2000, Hensolt and Brabb 1990, Yates et al. 1990, Phillips et al. 1993). Based on this information it is difficult to accurately determine the basin thickness and the amount of groundwater in storage.

(II) Aquifer Distribution:

The first hydrogeologic study done on a part of the Westside Basin was by Kirker Chapman and Associates (1972). In this investigation, they regarded the Merced

Formation as horizontally layered and omitted the folded area of the Merced Formation along the coastal bluffs in Daly City and along the San Andreas fault. Consequently, Based on water level and pump test data within their study area they considered the whole aquifer as unconsolidated. Their conceptual model did not attempt to differentiate clay and sand layers of the Merced and Colma formations. Thus, they had a simplified model that did not delineate multiple unconfined and confined aquifers that are likely to occur in the region. Their model was supported by Boone, Cook and Associates (1987) for the Daly City part of the Westside Basin, but was rebuffed by different authors later on (Yates et al. 1990, Applied consultants 1991, Phillips et al. 1993, CH2MHill 1998, Bookman-Edmonston and Associates and Hydrofocus, Inc. 1998, Luhdorff and Scalmanini 2002).

Boone, Cook and Associates (1987) improved on the preexisting conceptual model because they incorporated in their model a gradual change in the Westside Basin from Daly City to San Bruno. For example, they noticed a higher content in clay and gravel in San Bruno and classified the Westside Basin as unconfined in the vicinity of Daly City and semiconfined near San Bruno. Their conceptual model was supported by detailed geologic cross sections where all clay, sand and gravel layers were assumed horizontally stratified. Unfortunately, Holocene aged surficial alluvial deposits and current surface water features (i.e. creeks) in the area were not incorporated into their model.

Yates et al. (1990) while studying the hydrogeology of Golden Gate Park and the Lake Merced area presented the concept of an upper unconfined aquifer and a lower confined aquifer. They regarded the shallow aquifer representing the water table in the basin as isolated from the underlying deep aquifer by a clay layer found at elevations between 7.3 and 28.7 meters below sea level. Yates et al. (1990) determined that the shallow aquifer is found in the sand dunes and Colma Formation since extensive clay layers are not present in these units. The deep aquifer they assigned to the Merced Formation since it contains interbedded clay beds. They correlated the clay layer that divided the two aquifers between the northern end of Lake Merced to Stern Grove Park. However, They stated that to the south, toward the San Francisco Golf Club and the Olympic Country Club, the clay layer might not be a continuous bed. In fact, based on logs for wells at both golf clubs, they identified different clay layers that did not seem to be continuous. Therefore, although Yates et al. (1990) determined the vertical gradient within the shallow aquifer overlying the main confining clay layer near the zoo to be negligible this might not be the case south of Lake Merced. In addition, Yates et al. (1990) considered the observed tilt of the Merced Formation along the coastal bluffs at Fort Funston and noted that such tilted fine-grained strata might significantly impede horizontal groundwater flow.

Applied Consultants (1991) also agreed with Yates et al. (1991) on this "dual" shallow-deep aquifer system for the Westside Basin. However, they considered the deep aquifer to be semi-confined. They argued that the discontinuous aquitards formed by clay layers allowed recharge from the shallow to the deep aquifer.

Luhdorff and Scalmanini (2002) modified this dual aquifer system model and regarded the Westside Basin as consisting of several aquifer units. In addition, they pointed out the necessity of a better understanding of the hydrostratigraphic conditions in the Westside Basin. They considered in their cross sections that the Merced Formation is tilted to the northeast along the coastal bluffs in Daly City but regarded it as flattening out further inland. As a result of their interpolation, they identified a shallow estuary or lagoonal clay under Lake Merced, which extended to about 30 meters below land surface. They assumed that this clay layer might be responsible for the isolation of aquifer units lying below Lake Merced from those along the coastal section. In addition, Luhdorff and Scalmanini (2002) also identified other clay layers lower in the Merced Formation and tentatively correlated them with Clifton and Hunter's (1987, 1988, 1992, 1999) sequences. They concluded that the source of the water in the aquifers units the sand-rich sediments in the upper part of the Merced Formation. This interpretation agrees with Potter's (1999) conclusion (discussed in section 3.2) for the source material of water samples collected from different wells in San Bruno. However, their geologic interpretation of the basin does not take into consideration the folding of the Merced Formation west of the Serra fault. Finally, Luhdorff and Scalmanini (2002) determined that the clay layers of the Merced Formation become thin and discontinuous southward from Daly City, and suggested that the aquifer systems from Colma southward could be classified as being unconfined. This interpretation of the aquifer conditions in the Westside Basin is exactly the opposite of how Boone, Cooks and Associates (1987) envisioned the basin; i.e. unconfined in Daly City and semiconfined near San Bruno.

In summary, The Westside Basin is composed of several water bearing units, which are delineated by the different sand and clay layers of the Merced and Colma formations. Although the thickness and extent of these sand and clay layers may vary, they will undoubtedly create different water bearing zones. Thus, an upper unconfined aquifer exists which is underlain by several deep aquifers. The conceptual model for the Westside Basin (Figure 3.1) shows the different geologic units in the basin, which form the different water bearing zones. Groundwater movement shown in the model is discussed below in section 3.3. Furthermore, water level and water quality data presented in this chapter corroborate this interpretation.

3.2 Methods and Materials

In order to collect water level and water quality data for the Westside Basin all the wells in the basin had to be identified and located. Wells in the Westside Basin were located with a Trimble ProXR GPS unit that has a submeter instrumental accuracy (Trimble 1999). All other wells, to which access was not possible, or that have been destroyed were located based on site location description mentioned in well logs, reports

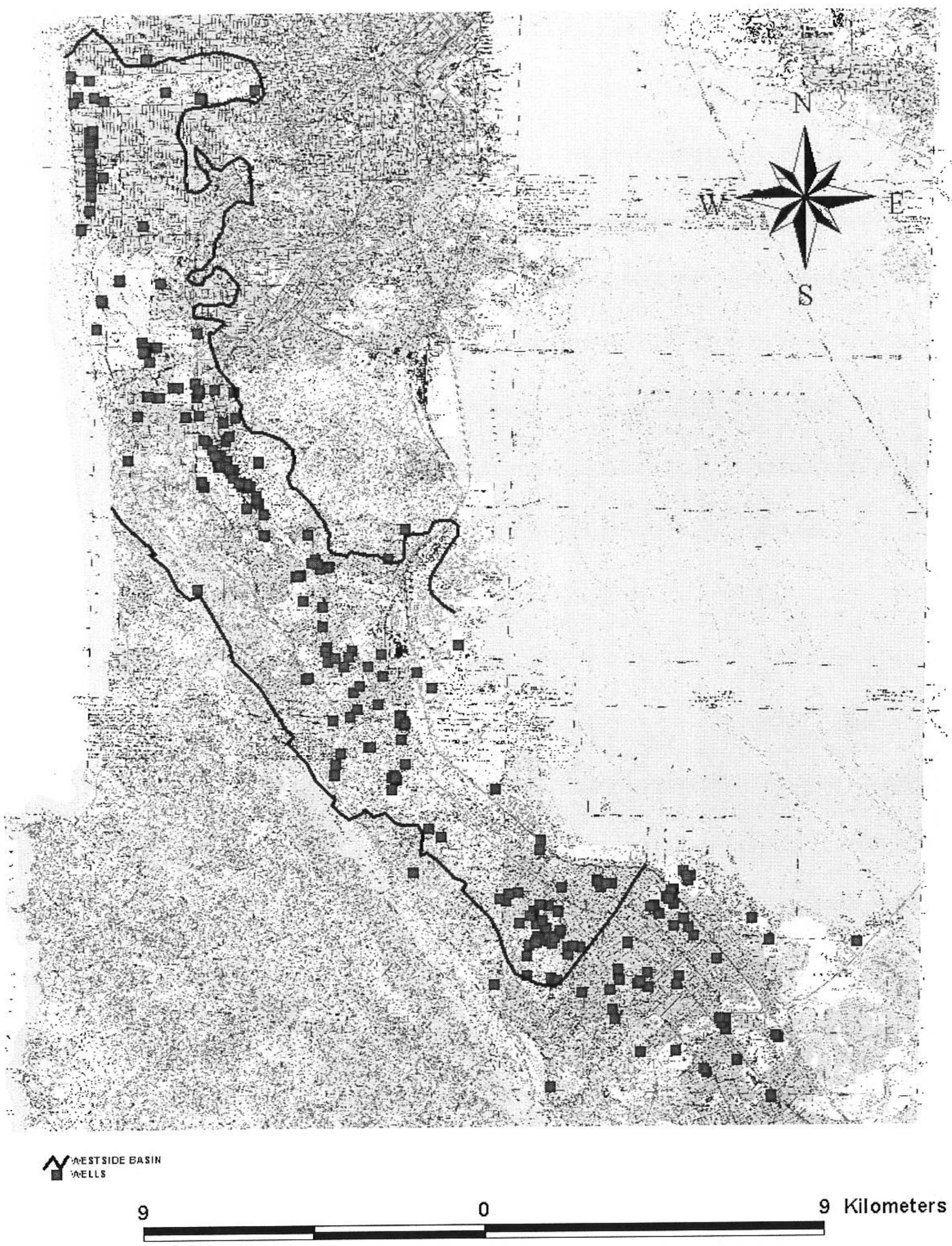


Figure 3.2: *Location of existing and former wells in the area stretching from Golden Gate Park in the north to San Mateo and Foster city in the South.*

or other records made available by San Mateo County Environmental Health, California Water Service Company, Daly City Water and Wastewater Department and San Bruno Public Works. Data analysis of well locations were compiled using ArcView 3.2. The map showing the location of all the wells (Figure 3.2) as well as all other maps generated using this program are in Albers Projection.

Water level readings are a useful tool to identify different hydrostratigraphic units, since through their interpolation on a regional scale groundwater flow direction within a unit can be determined. They also allow a better understanding of interconnectivity between the hydrostratigraphic units. However, it is important to emphasize that water level readings also depend on well construction and making sure static conditions are present, i.e., there is no pumping activity occurring nearby. Well screen intervals have to be taken into consideration when analyzing static water level readings. Only when a set of wells is screened in the same hydrostratigraphic unit can a clean and representative interpolation of the static water level be made. Unfortunately, despite attempts to isolate wells screened in different water bearing zones, such conditions are, in general, not available in the Westside Basin. Consequently, water levels within the Westside Basin can show steep downward gradients (Figure 3.3). Thus, potentiometric surface maps generated in this thesis represent a general water level for the basin.

The water level data presented in this thesis was collected by municipal water agencies (San Francisco Water Department, Daly City Water and Wastewater

Department, California Water Service Company and San Bruno Public Works, all of them hereafter called *Westside Basin Partners*) in April 2000, May 2001 and October 2001 (San Mateo County Environmental Health Division 2000, 2001a). Similar to other investigations (see for example, Kirker, Chapman and Associates 1972, Boone, Cooks and Associates 1987, Yates et al. 1990, Applied Consultants 1991, Phillips et al. 1993, CH2Mhill 1997, Luhdorff and Scalmanini 2002) the majority of the wells used were production wells (both municipal drinking water as well as irrigation wells) with different depths, and contrasting screen intervals. Therefore, it is possible that water level contours may contain errors caused by variation of hydraulic head with depth (Yates et al. 1990). San Mateo County Environmental Health Division (2000, 2001a) noted such errors in Golden Gate Park, Daly City, South San Francisco and San Bruno (Figure 3.3), where well in close proximity to one another and with screen intervals deeper than 100 feet showed significant differences in water level even after hours of pumping shutdown. It is important to note that a depth of 100 feet was considered by Phillips et al. (1993) as approximate for a distinction between a deep and a shallow aquifer.

Water level data collected in this thesis was collected during a 24 hour shut down of all pumping wells in the basin. This was done to avoid problems that arise when water levels are collected near pumping and production wells (Bookman, Chapman and Associates 1998, San Mateo County Environmental Health 2000, 2001a). These types of problems had been addressed by Kirker, Chapman and Associates (1972) but none of the subsequent studies (Boone, Cooks and Associates 1987, Yates et al. 1990, Applied Consultants 1991, Phillips et al. 1993, CH2Mhill 1997) had made a proper basin wide attempt to avoid them. Therefore, such interpretations are not representative of local static water level conditions. Thus, the water level data collected by the Westside Basin Partners (San Mateo County Environmental Health 2000, 2001a) can be regarded as more representative of static water level conditions in the Westside Basin.

Most of the water level data was collected manually using electronic sounders with one hundredth of a foot increments. However, in April 2000 pressure transducers (In Situ mini TROLL) with data loggers were installed in some wells. For each monitoring event, the maps and associated piezometric surface (Figure 3.3) were generated using ArcView version 3.2, with the ArcView Spatial Analyst version 2.0 extensions. In using the ArcView software, groundwater elevations were interpolated between wells using Inverse Distance Weighted (IDW) interpolation. The IDW method requires a grid of points within a predetermined coordinate system where each cell has a preset size. Within this grid there are cells representing water level measuring points *p* with water levels L_p and cells *g* for which water levels L_g are determined. As shown in equation [1], for each individual L_g a predetermined number *n* of neighboring points *p* is used to calculate the weight w_{gp} of each point *p* with water level L_p.

[1] $$L_g = \sum_{p=1}^{n} w_{gp} * L_p$$

The weight w_{gp} is a function of the distance d_{gp} between points *g* and *p* [2]. Points *p* that are closer to *g* have a higher weight than those that are farther away (i.e., inverse distance weighted). The power parameter *b* in the IDW interpolation controls the significance of the surrounding points upon the interpolated value.

[2]
$$w_{gp} = \frac{d_{gp}^{-b}}{\sum_{P=1}^{n} d_{gp}^{-b}}$$

The distance d_{gp} between points g and p is calculate based on a preset coordinate system with X easting values and Y northing values. The square of the difference between X and Y values is summed up and the square root of the sum gives the distance d_{gp} [3].

[3]
$$d_{gp} = \sqrt{(X_g - X_p)^2 + (Y_g - Y_p)^2}$$

The number of neighboring points n used for these interpolations was set to 12. The power parameter b was set at 2 and the cell size was arbitrarily chosen to be 96.5 meters. Spatial analyst 2.1 uses a barrier input line theme to break and limit the interpolation points. Based on known and inferred geologic and hydrogeologic features, the San Andreas and Serra faults were defined as barrier themes in the interpolation. ArcView generated contour lines were adjusted slightly to correct for obvious edge effects along defined boundaries and where data was obviously limited.

Water quality parameters are also a very useful tool in identifying different hydrostratigraphic units. For example, wells that are screened at different depths can, at times, show different concentrations of a chemical constituent. This has been reported for several wells in the Westside Basin (Yates et al. 1990, Phillips et al. 1993, Guidetti and Schaefer 1995, San Mateo County Environmental Health Division 2001a, 2002a, 2002c). Therefore, it is imperative to identify wells screened at a similar depth and that, consequently, show similar concentrations for particular constituents. Using this information in conjunction with local stratigraphy and water level data, aids in the delineation of different hydrostratigraphic units. However, due to various well construction designs in the Westside Basin, it is difficult to identify wells screened in one water-bearing zone. Oftentimes, production wells are designed for maximum possible water production. Therefore, they are screened throughout several water bearing zones. Consequently, water quality results represent a composite sample that may have been drawn from numerous hydrostatigraphic units. Without question, the best possible way of differentiating water bearing units is by looking at the top of the screen interval for a given well. Once again there were a very limited number of wells that afforded us this luxury; thus I could not use this approach to separate the various aquifer units. Wells with a deeper top of screen interval will have different water chemistry than wells with a shallower water screen interval. Therefore, the precise delineating of different hydrostratigraphic units is not feasible and only an approximate subdivision as proposed in chapter 5 can be made.

Water quality samples were collected by the Westside Basin Partners in May 2000, April 2001 and October 2001 (San Mateo County Environmental Health Division 2001a, 2002a, 2002c). For all production wells samples were collected at taps located close to the wellheads. Samples collected at monitoring wells were bailed. For each well a set of bottles was provided by the lab. Some bottles contained no preservatives and some contained either HCl or HNO_3 as a preservative. All samples were submitted to the lab on the same day they were collected. A total of 52 samples were collected. Samples collected in May 2000 were analyzed by Sequoia Analytical. The lab followed Regional Water Quality Control Board guidelines and analytical methods set by the Environmental Protection Agency (EPA). In addition, a blank was run for every sample bottle. Furthermore, for every 10th sampling location a second set of samples was collected and sent to the lab. The location for duplicate samples was not disclosed to the lab. Thus, we could use duplicate samples as an internal means of quality assurance. The results were almost identical in most cases. Moreover, Sequoia Analytical reported relative percent difference (RPD) values for each batch of samples they analyzed. The average RPD value was used as the percentage number for the error bars presented in May 2000 plots (see section 3.3). In addition to the RPD values, a cation-anion balance for all sampling points was determined. A comparison between the RPD values with cation-anion balance for the 2000 samples shows a discrepancy. The RPD values seem to indicate that most of the results are below the 5% error margin. However, the QA/QC analysis indicates that 28% of the results are above the 10% error margin and 15% fall between the 5-10% error margin. It is possible that certain analytes that were not analyzed by the lab were present in the water samples. The presence of these analytes would explain the higher error margin found in the cation-anion balance. Furthermore, we cannot rule out the possibility that analytical errors were generated by the lab itself.

Samples collected in April 2001 and October 2001 were analyzed by San Francisco Water Department's lab in Millbrae. RPD values were only reported for the cations of the samples collected in April 2001. Cation-anion balances were determined for all sampling sites in April 2001 and October 2001. For the samples collected in April 2001, 50% of the results were above the 10% error margin and 18.5% are between the 5 and 10% error margin. For the samples collected in October 2001, 35% fall within the 5 to 10% error margin. Again, human error or the presence of analytes not detected in the water most likely explain the reason for such discrepancies.

In this chapter different water quality parameters that are considered (i) major inorganic cations and anions as well as (ii) analytes that are precursors for potential saltwater intrusion are discussed. The discussed constituents include chloride, bromide, boron, sulfate, nitrate, calcium and potassium.

3.3 Results and Discussion

3.3.1 Water Level

In April 2000, Westside Basin Partners and private well owners, agreed to shut down their wells in the Westside Basin for a period of 24 hours (San Mateo County Environmental Health 2000). Water level measurements were taken prior to well shutdown as well as prior to resumption of pumping activities. Figure 3.3a shows the resultant water level contour map for that basin wide water level response test. This test yielded the best approximation of static water level conditions in the deeper aquifers of the Westside Basin. As observed by previous authors (Kirker, Chapman and Associates

1972, Boone, Cooks and Associates 1987, Yates et al. 1990, Applied Consultants 1991, Phillips et al. 1993, CH2Mhil 1997, Luhdorff and Scalmanini 2002) and presented in the conceptual model for the basin (Figure 3.1) water level conditions of the deep aquifers in San Francisco indicate a general east-west flow towards the Pacific Ocean. This trend changes gradually in the Lake Merced area, where groundwater flow changes first to the south and then to the southeast. In Daly City, Colma, South San Francisco and San Bruno the lowest water level conditions occur in the "central axis" of the Buri-Buri Valley. From San Bruno Mountain groundwater flows to the southwest and south to the "central axis" of the Basin prior to flowing southeastward. Applied Consultants (1991), Phillips et al. (1993), CH2Mhill (1997) and Luhdorff and Scalmanini (2002) suggested that groundwater flow from the Buri-Buri Ridge behaves in a similar way as along the San Bruno Mountain, i.e. flowing first toward the "central axis" of the basin prior to flowing southeastward. This interpretation, though plausible, is not confirmed by any water level readings due to a lack of wells along and at the base of the Buri-Buri Ridge. Nevertheless, this interpretation has also been incorporated in the conceptual model of the Westside Basin (Figure 3.1). Between Millbrae and Burlingame, groundwater flows north northwestward towards San Bruno. Despite these general observations, some locations (Figure 3.3) do show steep downward gradients. As described earlier, this results from interpolation of different water level readings for deep wells that are in close proximity to one another but that have different screening intervals. Therefore, the contour maps have to be seen as showing general trends in the basin.

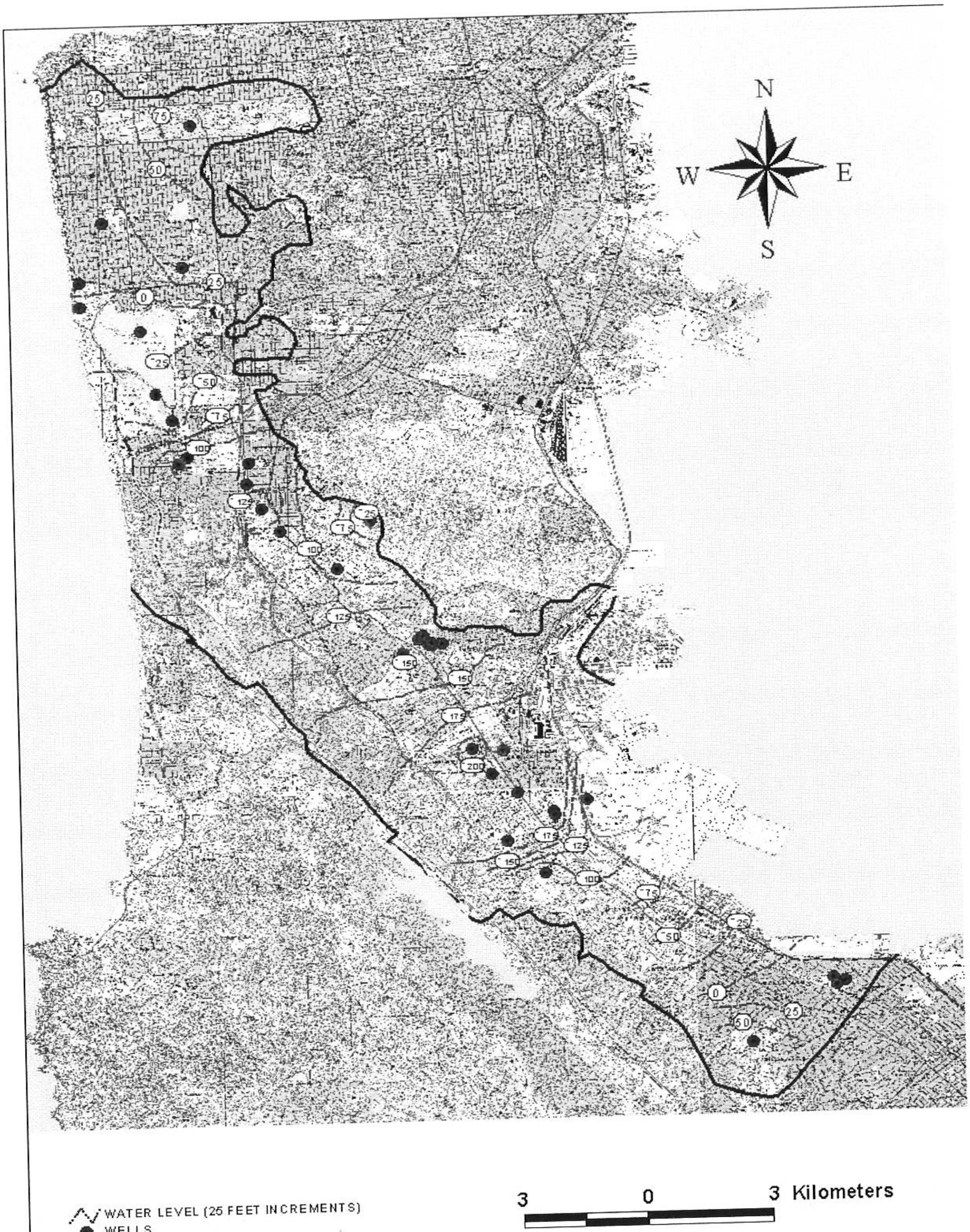


Figure 3.3a: *Water level conditions for the deeper aquifers of the Westside Basin on 04/28/00 after a 24-hour well shutdown. Source: San Mateo County Environmental Health Division (2000).*

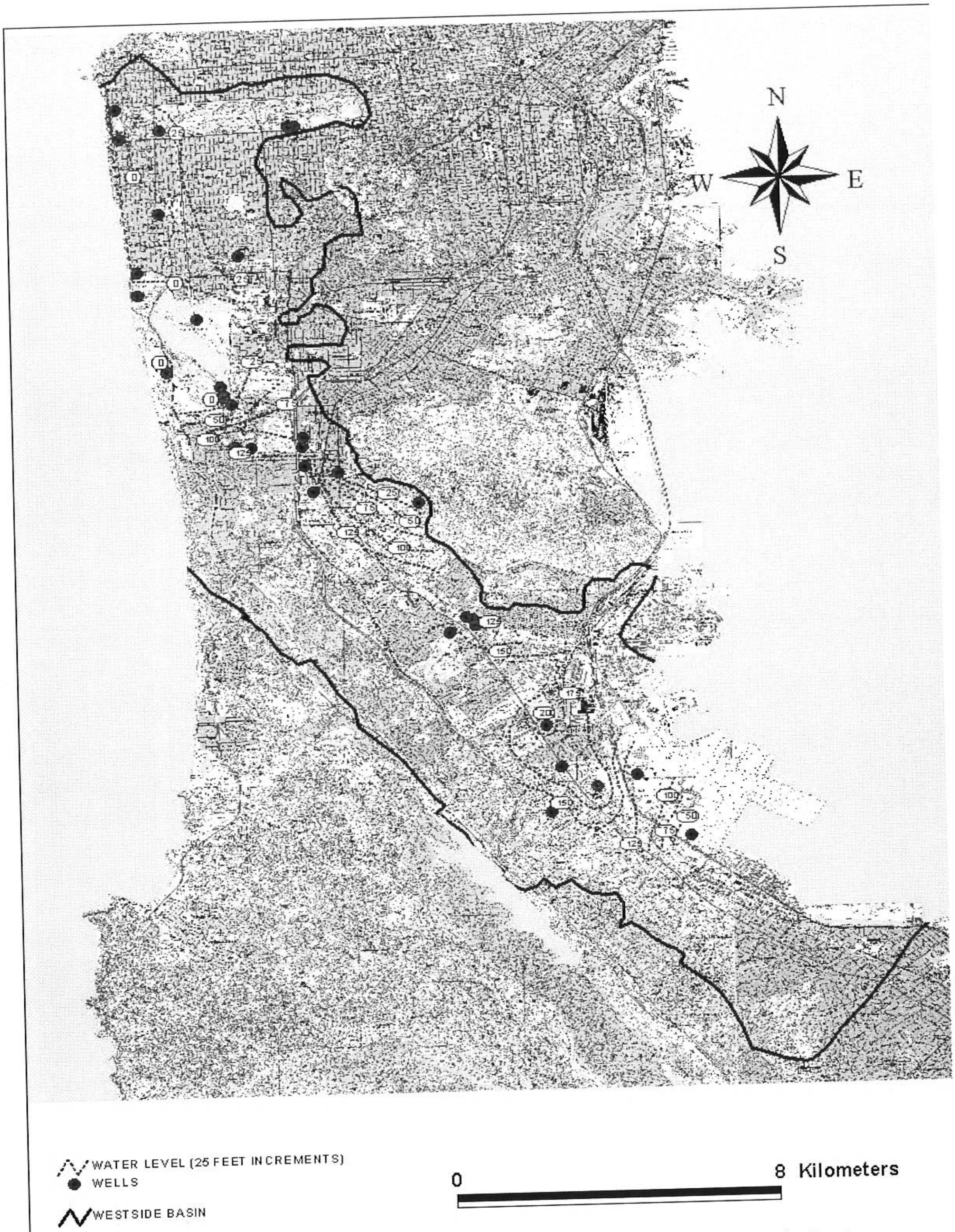


Figure 3.3b: *Water level conditions for the deeper aquifers of the Westside Basin on 04/26/01 after a 6-hour well shutdown. Source: San Mateo County Environmental Health Division (2001c).*

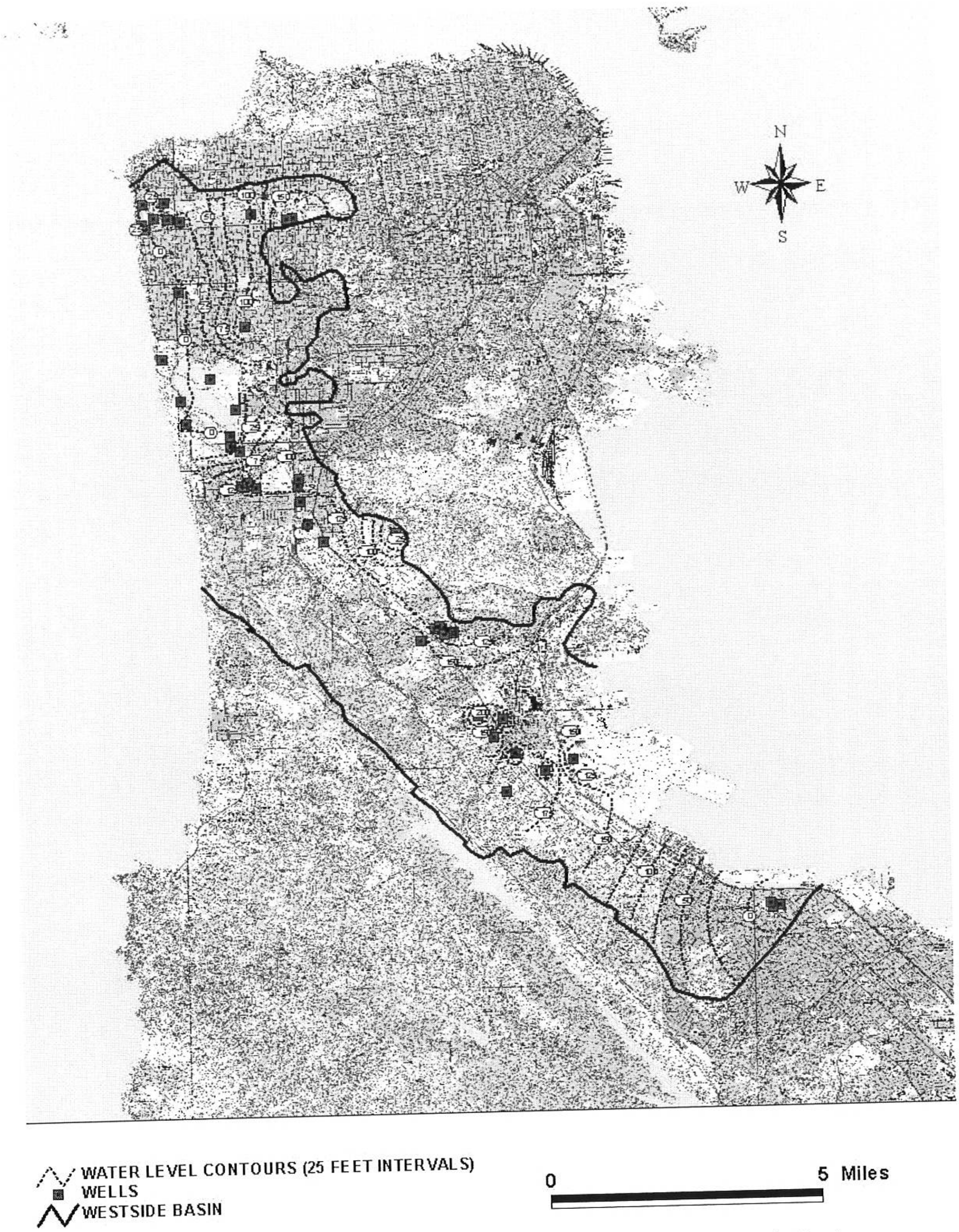


Figure 3.3: *Water level conditions for the deeper aquifers of the Westside Basin on 10/25/01 after a 6-hour well shutdown. Source: San Mateo County Environmental Health Division (2002b).*

Within the shallow aquifers groundwater in San Francisco tends to flow in an east-west direction towards the Pacific Ocean, i.e., in the same manner as in the deeper aquifers. A set of monitoring wells around Lake Merced and next to Pine Lake has shown that both lakes are in hydraulic connection with the shallow aquifer (Yates et al. 1990, Phillips et al. 1993, CH2Mhill, 1997, San Mateo County Environmental Health 2000, 2001, Luhdorff and Scalmanini 2002). Yates et al. (1990) suggested that Lake Merced creates a plateau in the water table by causing a path of low resistance for shallow groundwater flow. From South San Francisco southward to Burlingame groundwater within the shallow aquifers generally flows towards San Francisco Bay (Burns and McDonnell 2002).

3.3.2 Water Quality

In this section different water quality parameters that are considered (i) major inorganic cations and anions as well as (ii) analytes that are precursors for potential saltwater intrusion are discussed. The discussed constituents include chloride, bromide, boron, sulfate, nitrate, calcium and potassium.

3.3.2.1 Inorganic chemical constituents

Chloride:

Chloride is a major anion of seawater and moves through an aquifer at nearly the same rate as intruding water (Hem 1992). This conservative anion does not react in groundwater with other chemical constituents to form a precipitate or undergo exchange with other elements on clay surface (Hem 1985, Yates et al. 1990). Therefore, chloride concentrations can be used as an indicator of saltwater intrusion for areas where no other sources of chloride contamination exist (Guidetti and Schaefer 1995). Chloride concentrations in seawater are on average 19,400 mg/L (Seafriends 1997). However, in freshwater they are substantially lower. Rivers, on average, show a concentration of 7.8 mg/L (Seafriends 1997). The EPA has set a secondary maximum concentration level (SMCL) for chloride at 250 mg/L. Furthermore, the agricultural water goal for chloride concentrations is 106 mg/L (Ayers and Westcost 1985). Chloride concentrations above 500 mg/L are considered corrosive (Driscoll 1995).

Additional sources of chloride contamination in the environment include leaking sewer lines, chlorinated organic compounds and connate water from marine deposited sediments. Chloride derived from leaking sewage can be identified by correlating chloride, nitrates and boron in groundwater (Yates et al. 1990). The chloride and nitrate relationship is easily identified when chloride is plotted against nitrate and a linear relationship exists. In addition, chloride-to-boron ratios can be determined and compared with that of sewage. Chloride versus nitrate diagrams and chloride-to-boron ratios for water samples collected by the Westside Basin Partners (San Mateo County Environmental Health Division, 2001a, 2002a, 2002c) are shown Figure 3.7 and Table 3.3, respectively, and discussed are further below.

In heavily urbanized areas chloride can be introduced to groundwater in form of chlorinated organic compounds. The best way to identify chloride derived from such substances is by analyzing for chlorinated organic compounds.

The presence of chloride derived from connate water can be inferred by observing trends in chloride concentration over long periods of time. Differing from saltwater intrusion where an abrupt increase in chloride concentration can be noticed, flushing of connate water will cause a gradual increase of chloride concentration over time (Applied Consultants 1991).

Chloride concentrations for various wells in the Westside Basin are shown in Figure 3.4 and Table A.1 in Appendix A. The data, collected by the Westside Basin Partners and compiled by San Mateo County Environmental Health (2001a), confirms observations noted by previous authors in the area. Chloride concentrations vary considerably, at times even for wells that are located in close proximity to each other. It is important to note that wells located close to each other are screened at different levels and also have different water levels. This suggests that the presence of different aquifer zones can be delineated. Therefore, no chloride concentration contours were generated in

Figure 3.4 since they would produce an incorrect representation of the chloride distribution in the basin.

In general, in the Westside Basin, shallow groundwater zones show higher chloride concentrations than deeper zones. In the opinion of Phillips et al. (1993) water quality in the basin is controlled by geologic rather than by urban activities. Guidetti and Schaefer (1995) went further and argued that for the San Bruno area the difference in chloride concentration is evidence that the deeper aquifer zones are confined while the shallow zones are unconfined. Yates et al. (1990) determined that in San Francisco chloride concentrations average about 80 mg/L in wells 36 meters deep or less while deeper wells showed an average chloride concentration of 47 mg/L.

Data compiled by San Mateo County Environmental Health (2001a, 2002a) for May 2000 and April 2001 noted similar observations in chloride concentrations. For example, average chloride concentrations for deep wells in San Francisco were 44 mg/L and 47 mg/L in May 2000 and April 2001, respectively, and 74 mg/L and 84 mg/L for shallow wells. In San Mateo County, however, chloride concentrations for the deeper aquifer zones are, locally, higher than in San Francisco. Data compiled by San Mateo County Environmental Health (2001a, 2002a) indicates that average chloride concentrations for deep wells in Daly City and Colma were 68 mg/L and 76 mg/L in May 2000 and April 2001, respectively. Deep wells in San Bruno showed average chloride concentrations of 80 mg/L and 79 mg/L in May 2000 and April 2001, respectively. California Water Service Company wells in South San Francisco show the highest chloride concentrations among deep wells in the Westside Basin. Chloride concentrations, there, range between 91 mg/L and 160 mg/L. Applied Consultants (1991) noted that higher chloride concentrations could be due to flushing of connate water, reflecting the marine sediment environment, in which the Merced Formation was deposited. The shallow aquifer zones at San Francisco International Airport show much higher chloride concentrations than in San Francisco. Phillips et al. (1993) noted that at the San Francisco International Airport chloride concentrations exceed the secondary maximum contamination level (SMCL) of 250 mg/L. Burns and McDonnell (2002) confirmed this observation at several monitoring wells at the airport where chloride concentrations were as high as 4700 mg/L. Furthermore, Phillips et al. (1993) pointed out that correlation of chloride concentrations with nitrate and boron concentrations indicate contamination by sewage and seawater. On the other hand, Yates et al. (1990) showed that in the Golden Gate Park and Lake Merced areas there was a lack of correlation between nitrate and chloride indicating that sewage was not likely the cause of the chloride detected. They tentatively attribute the presence of chloride in the groundwater to sea spray and connate water. In addition, Lake Merced, where chloride concentration is enriched due to evaporation effects, seems to be in direct connection with the shallow aquifer zones (Phillips et al. 1993). Shallow wells located south of the lake, and, therefore, downgradient of it, are enriched in chloride, compared to shallow wells upgradient of the lake (Yates et al. 1990).

Overall, chloride concentrations found in the basin in May 2000, April 2001 and October 2001 indicate an increase in chloride concentration with depth. This observation

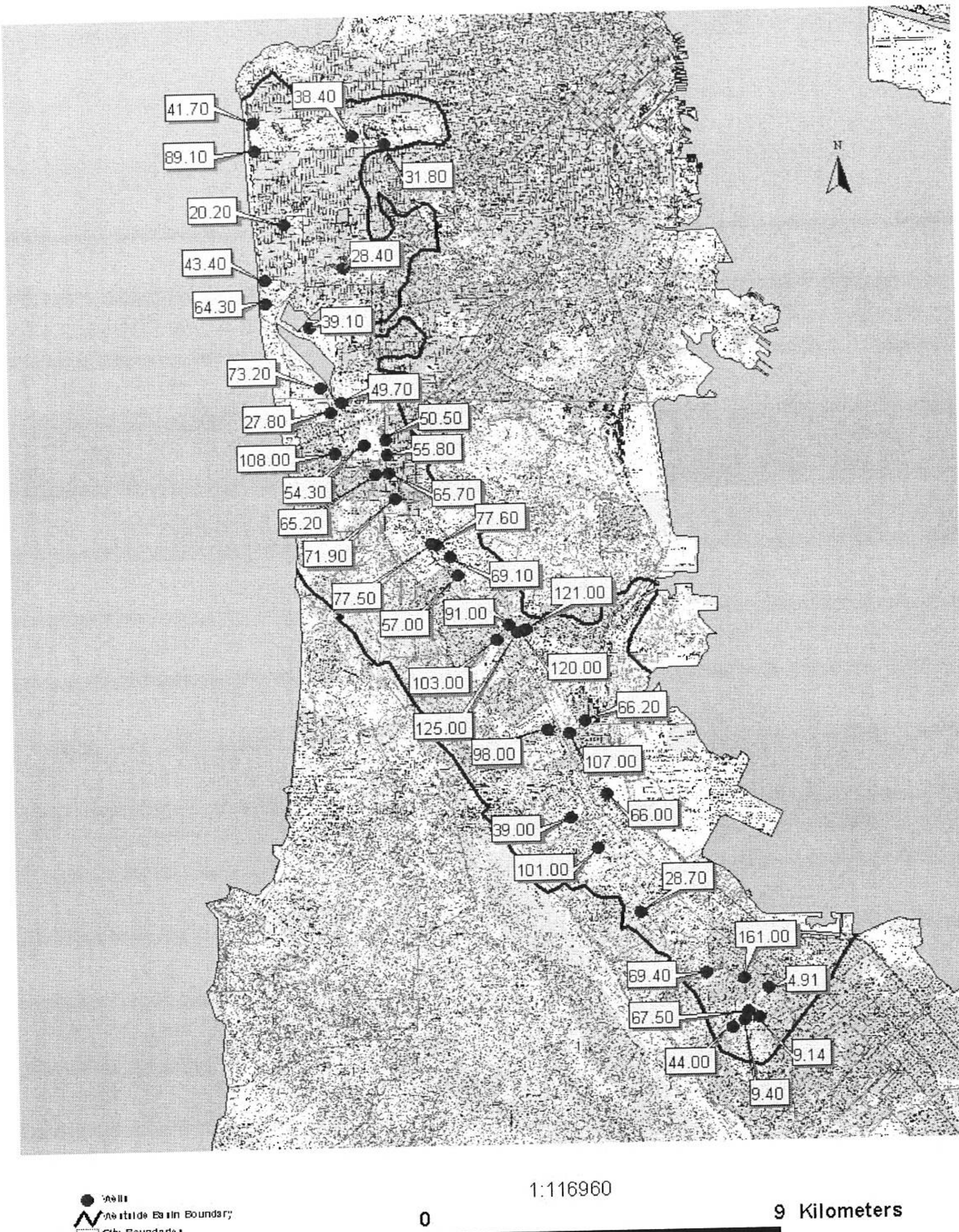


Figure 3.4a: *Chloride concentrations for wells sampled by Westside Basin Partners in May 2000. Since there is no differentiation between wells drawing from different water bearing zones no chloride concentration contours have been interpolated. Source: San Mateo County Environmental Health (2001a).*

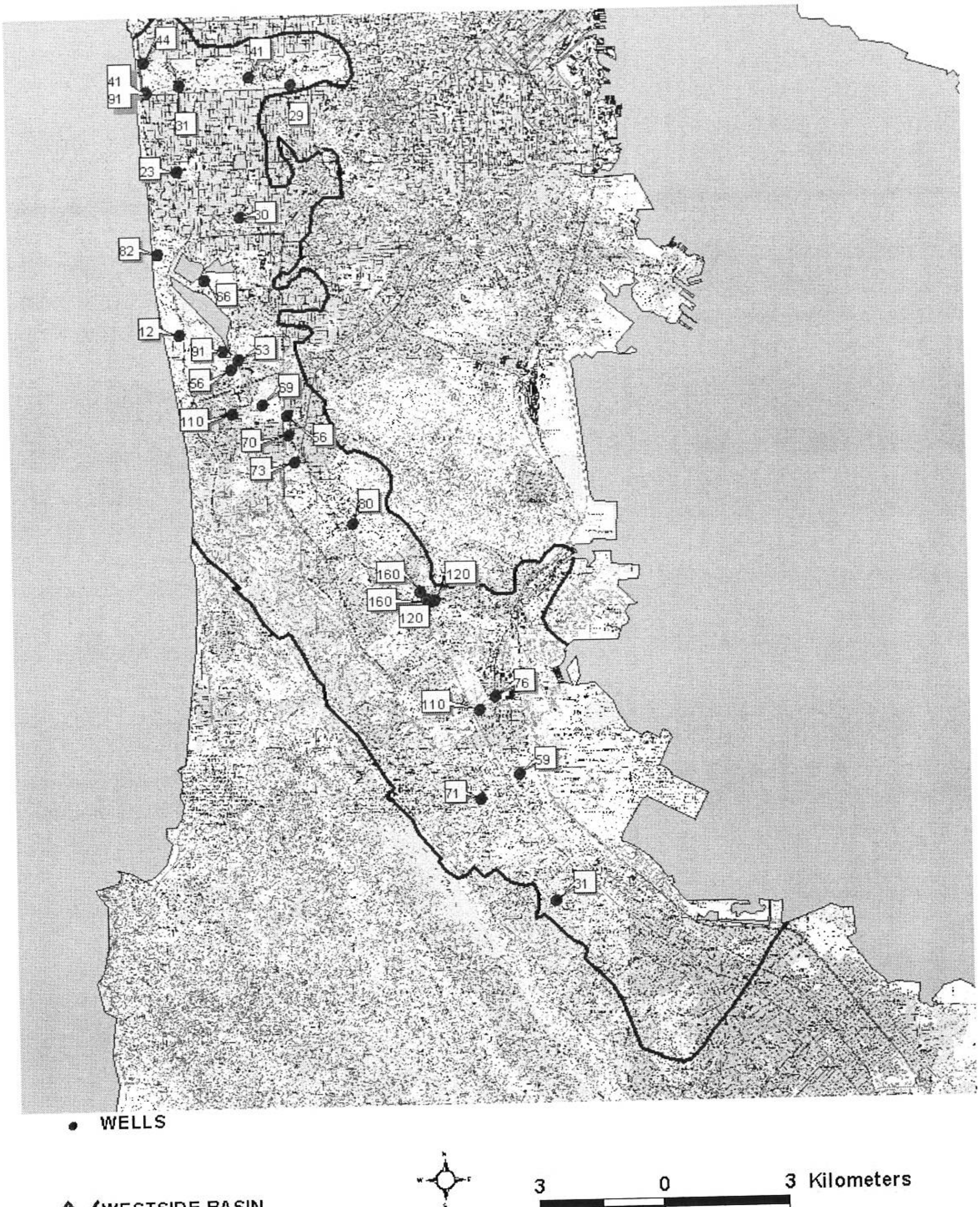


Figure 3.4b: *Chloride concentrations for wells sampled by Westside Basin Partners in April 2001. Since there is no differentiation between wells drawing from different water bearing zones no chloride concentration contours have been interpolated. Source: San Mateo County Environmental Health (2002a).*

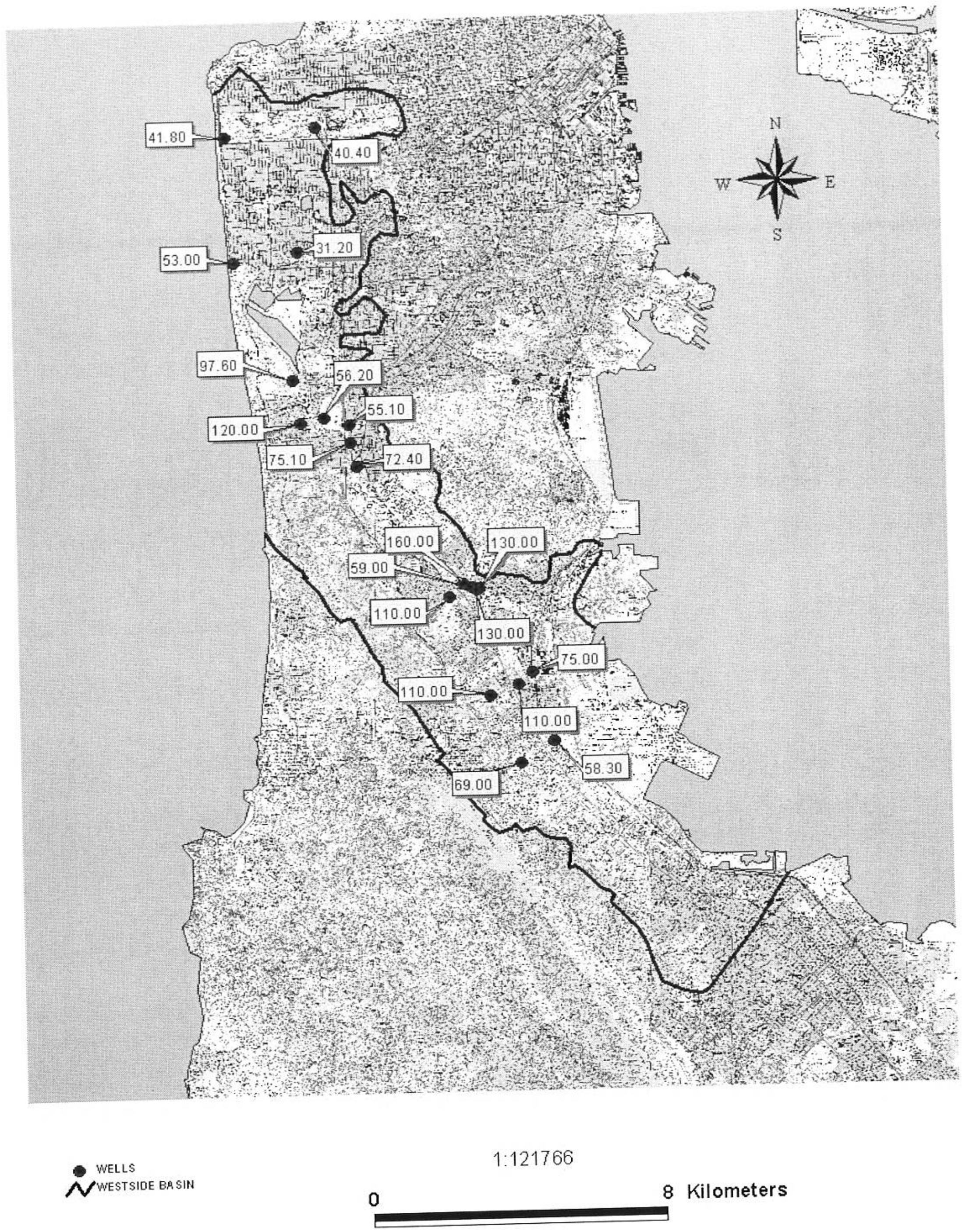


Figure 3.4c: *Chloride concentrations for wells sampled by Westside Basin Partners in October 2001. Since there is no differentiation between wells drawing from different water bearing zones no chloride concentration contours have been interpolated. Source: San Mateo County Environmental Health (2002c).*

is most noticeable among wells located in close vicinity to each other and that have different screen intervals. An exception to this are wells in the vicinity of Lake Merced and wells with very shallow screen intervals at the San Francisco International Airport. In the Lake Merced area wells seem to be influenced by the lake, which is enriched in chloride due to evaporative effects on the lake surface. At the San Francisco International Airport shallow wells are installed in artificial fill and Young Bay Muds. The high chloride concentrations may be due to seawater, sewage or other sources of chloride found in the artificial fill.

Bromide:

Bromide is another major ion found in seawater that has an average concentration of 65 mg/L (Hem 1992). Chloride-to-bromide concentrations in seawater are around 300. This ration can be used to determined potential seawater intrusion. However, unlike chloride, bromide is not a conservative constituent in groundwater. Since the bromide ion is larger than the chloride ion, bromide may be selectively concentrated by clay-membrane effects (Hem 1985). In addition, other sources of bromide, e.g., gasoline additives and ethylene dibromide, can contribute bromide to groundwater (Philips et al. 1993). Therefore, for urbanized areas chloride-to-bromide ratios cannot be the only means to determine seawater intrusion.

In the Westside Basin chloride-to-bromide ratios were first determined by Phillips et al. (1993). They collected samples from different wells in San Francisco and at the

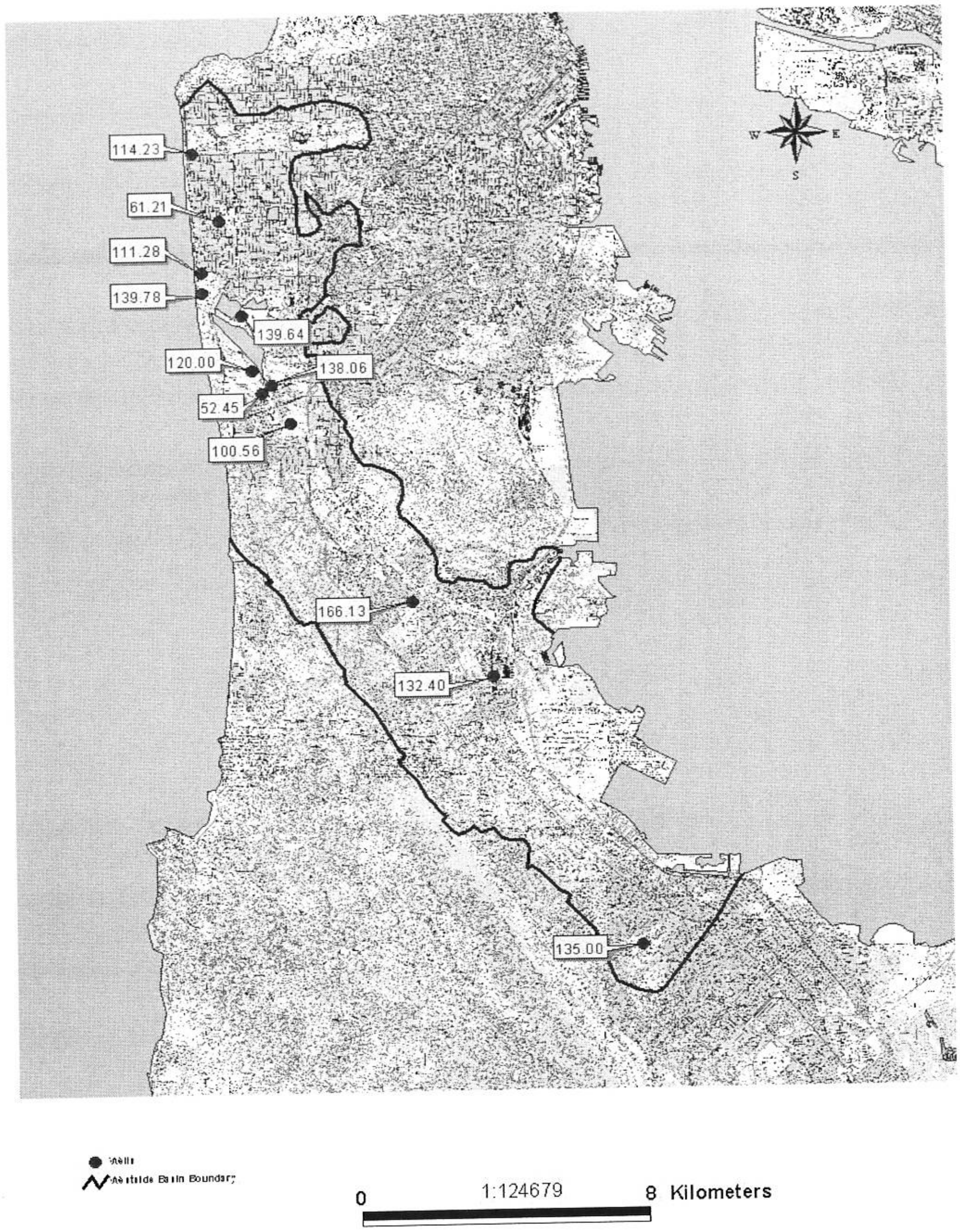


Figure 3.5a: *Chloride-to-bromide ratios for wells sampled by Westside Basin Partners in May 2000. Since there is no differentiation between wells drawing from different water bearing zones no chloride-to-bromide ratio contours have been interpolated. Note that that chloride-to-bromide ratio around 300 can be indicative of seawater intrusion.*

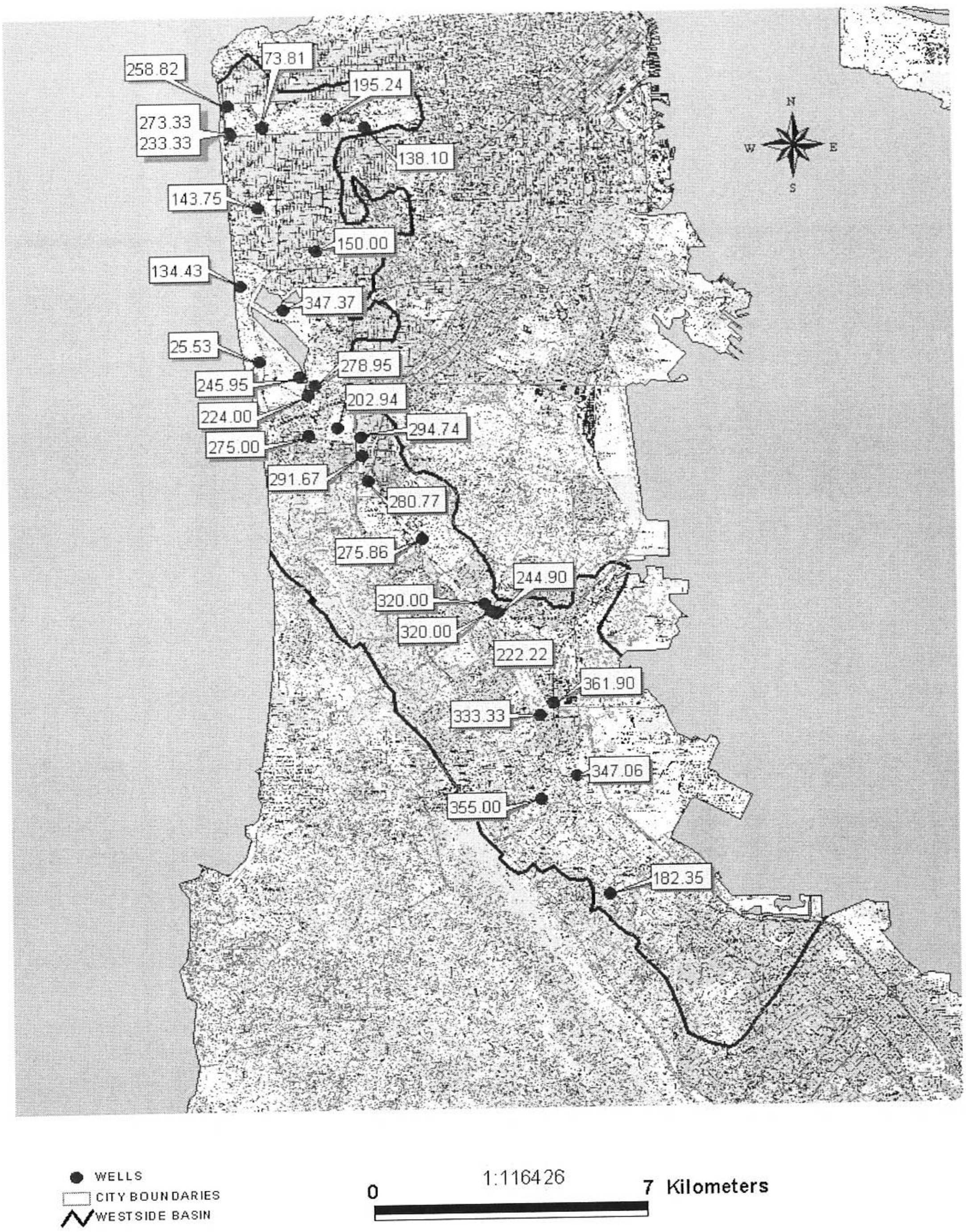


Figure 3.5b: *Chloride-to-bromide ratios for wells sampled by Westside Basin Partners in October 2001. Since there is no differentiation between wells drawing from different water bearing zones no chloride-to-bromide ratio contours have been interpolated. Note that that chloride-to-bromide ratio around 300 can be indicative of seawater intrusion.*

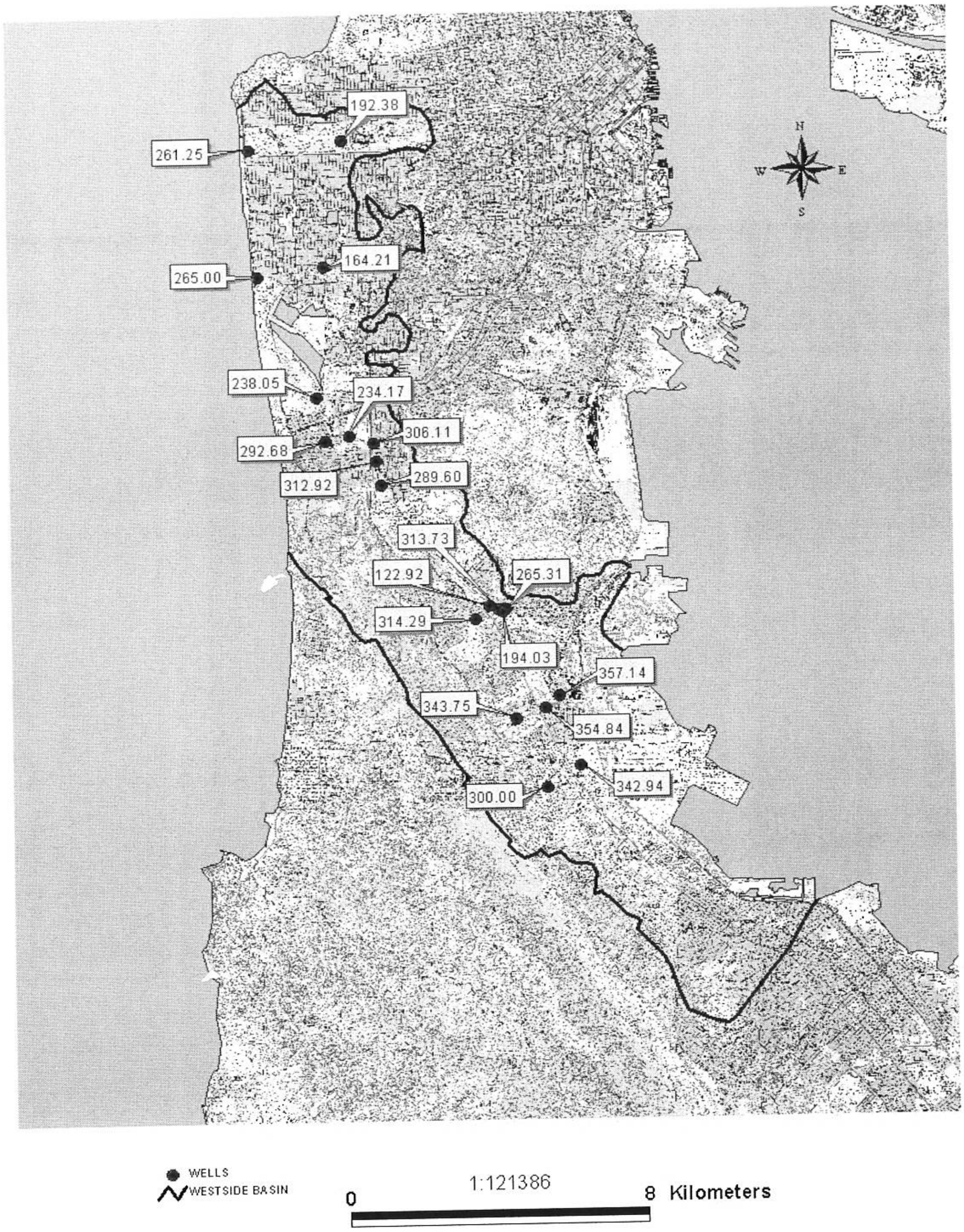


Figure 3.5c: Chloride-to-b*romide ratios for wells sampled by Westside Basin Partners in October 2001. Since there is no differentiation between wells drawing from different water bearing zones no bromide concentration contours have been interpolated. Note that that chloride-to-bromide ratio around 300 can be indicative of seawater intrusion.*

San Francisco International Airport and pointed out that the chloride-to-bromide ratios at the South Windmill well in the Golden Gate Park and at the USGS-D well at the San Francisco International Airport were similar to that of seawater. Samples collected by the Westside Basin Partners in 2000 and 2001 (San Mateo County Environmental Health Division 2001a, 2002a, 2002c) do corroborate these findings for the South Windmill well. Chloride-to-bromide ratios in this as well as in various wells in the Westside Basin (Figure 3.5 and Table A.2, Appendix A) are close or higher to that of seawater. However, as mentioned above these values cannot be used as sole indicators for presence of seawater intrusion. Other parameters discussed further ahead have to be taken into consideration.

Boron:

Boron, another constituent common to seawater, typically averages 4.5 mg/L (Phillips et al. 1993, Leeman and Sisson 1996). Its geochemical behavior is similar to chloride. It is a conservative anion and when used in a chloride-to-boron ratio it is a useful tool for identifying seawater intrusion in a groundwater system. This, of course, is only useful as long as there are no other sources of extraneous boron found in a given system. One additional source of boron is from sewage, which contains high concentrations of borax cleansers and sodium perborate (as bleach) (Kehew 2000). However, the chloride-to-boron ratios of seawater (4,220) and sewage (400 to 500) differ considerably (Phillips et al. 1993). In addition, sewage input to the groundwater can be confirmed by supplemental analysis of groundwater for methylene blue active substances

(MBAS), which are common substances found in various detergents (Phillips et al. 1993). Another source of boron is fertilizers. If (i) low concentrations of boron are found in groundwater alongside low concentrations of MBAS, high concentrations of nitrate and (ii) if there is a correlation between sulfate and nitrate, it is likely that fertilizers carried by irrigation water impact groundwater. Discussion on MBAS, nitrates and sulfates can be found below.

Throughout the Westside Basin production wells show a high chloride-to-boron ratio; these ratios approach seawater ratios (Figure 3.6 and Appendix A, Table A.3). This observation was already noticed by Phillips et al. (1993) for the Olympic Country Club and San Francisco Golf Club. Most of the monitoring wells around Lake Merced also showed high chloride-to-boron ratios. There are, however, some notable exceptions. For example, production wells in Golden Gate Park do not show high ratios, despite Phillips et al. (1993) observation of high chloride-to-boron ratios at the Windmill wells (Appendix A, Table A.3). Two wells, USGS South Windmill D and LMMW4S showed ratios close to that of sewage (Appendix A, Table A.3), indicating that in certain areas sewage might be getting into the groundwater.

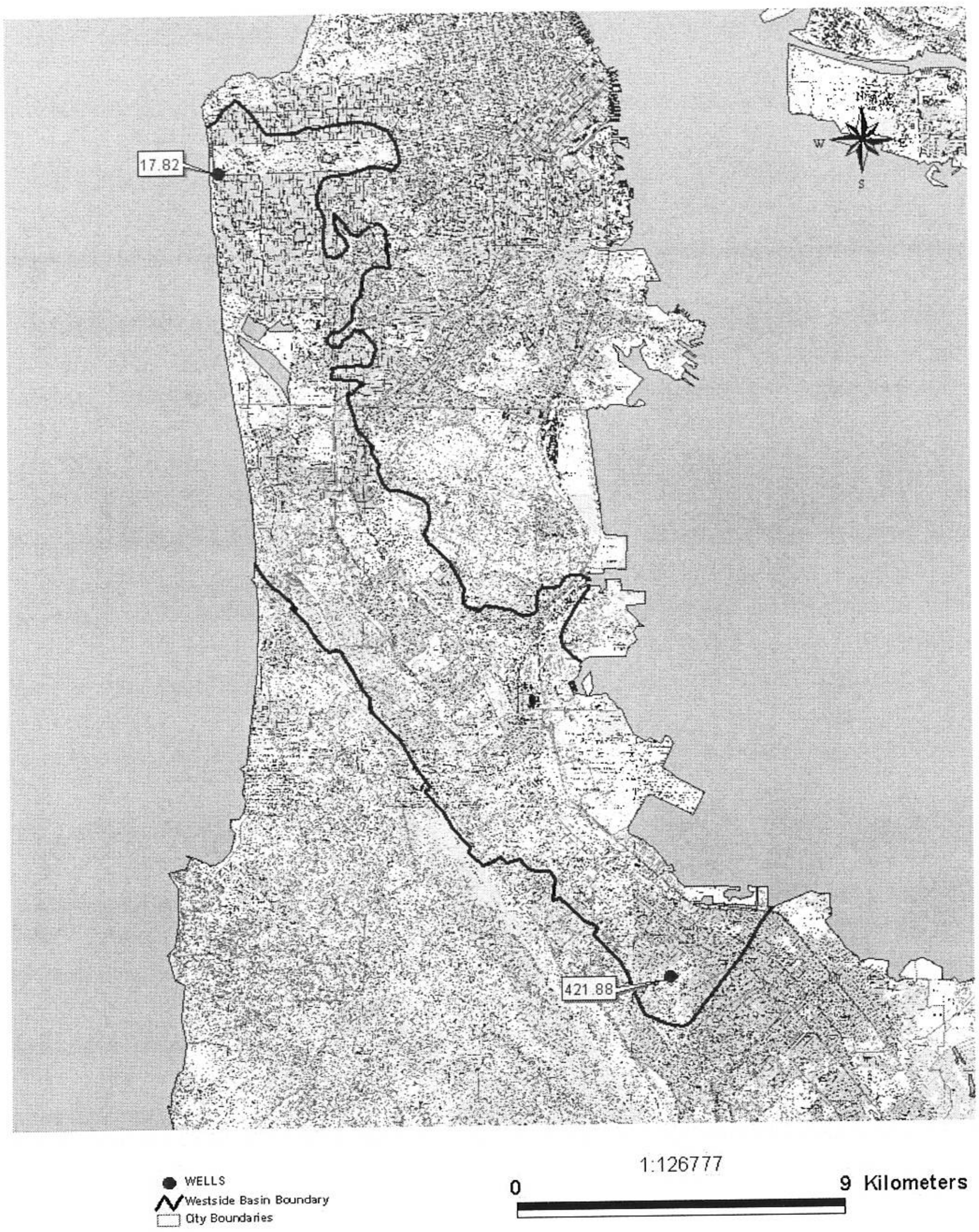


Figure 3.6a: *Chloride-to-boron ratios for wells sampled by Westside Basin Partners in May 2000. Since there is no differentiation between wells drawing from different water bearing zones no chloride-to-boron ratios contours have been interpolated. Note that concentrations close to 4220 can indicate presence of seawater and that ratios between 400 and 500 can indicate presence of sewage.*

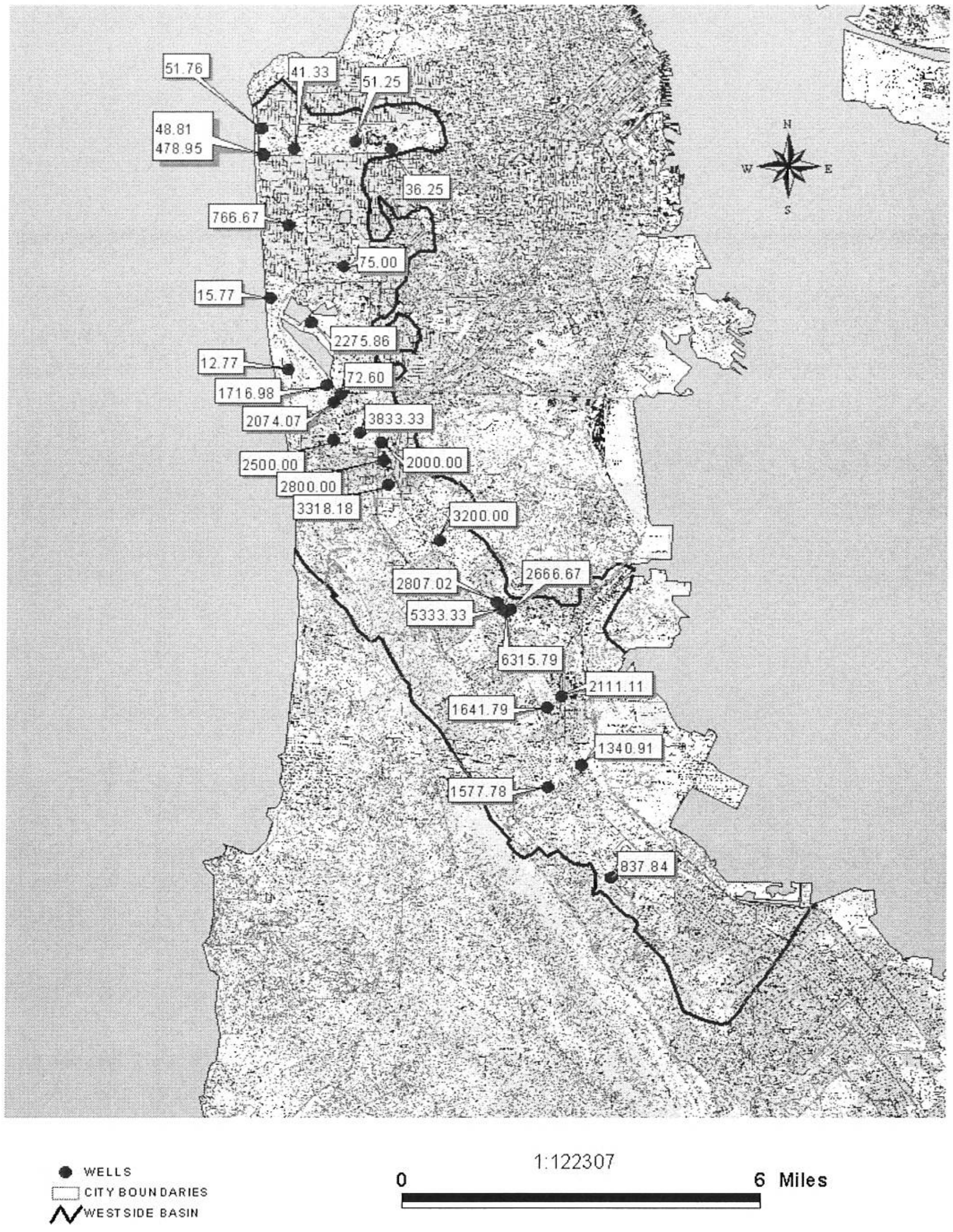


Figure 3.6b: *Chloride-to-boron ratios for wells sampled by Westside Basin Partners in April 2001. Since there is no differentiation between wells drawing from different water bearing zones no chloride-to-boron ratios contours have been interpolated. Note that concentrations close to 4220 can indicate presence of seawater and that ratios between 400 and 500 can indicate presence of sewage.*

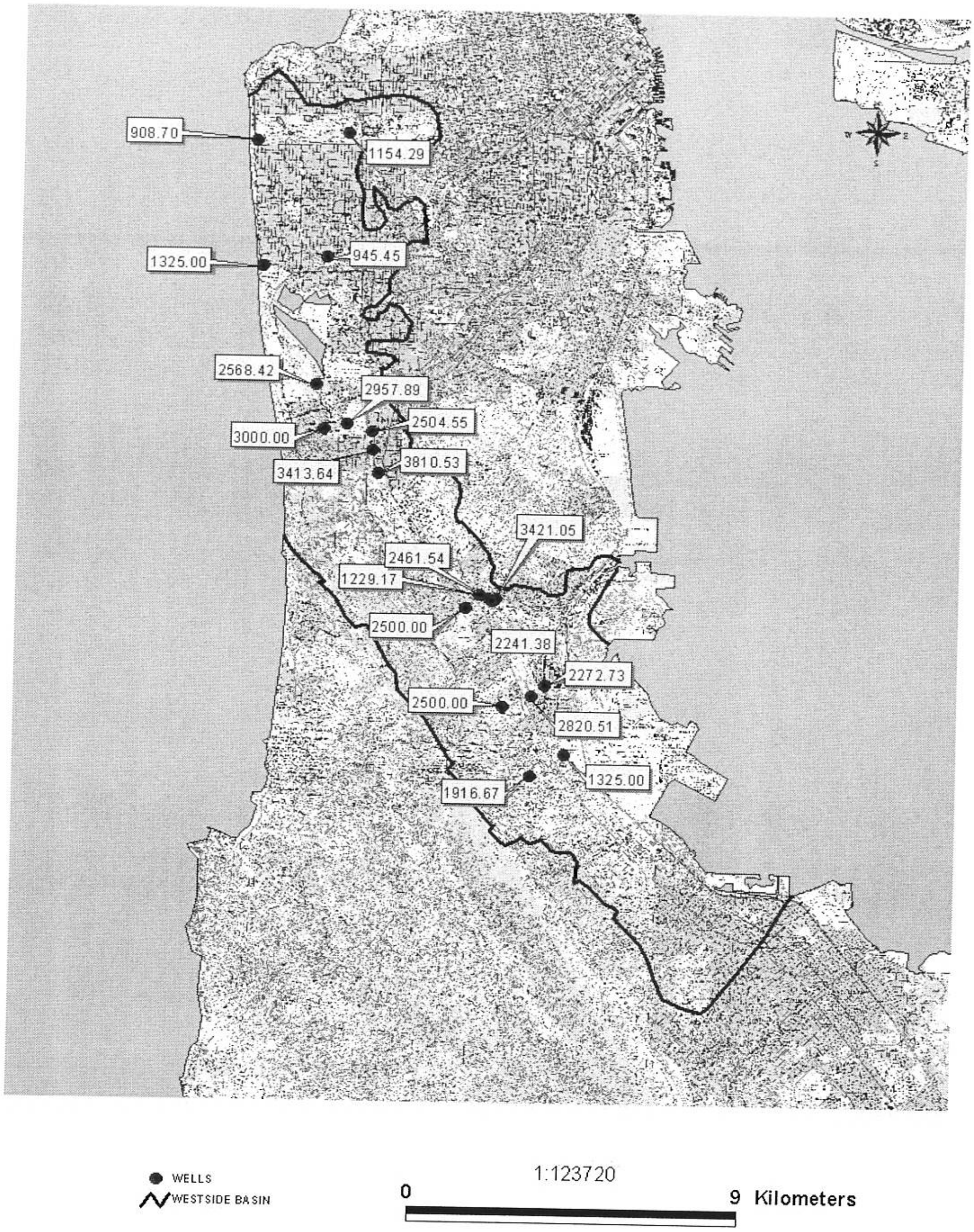


Figure 3.6c: *Chloride-to-boron ratios for wells sampled by Westside Basin Partners in October 2001. Since there is no differentiation between wells drawing from different water bearing zones no chloride-to-boron ratios contours have been interpolated. Note that concentrations close to 4220 can indicate presence of seawater and that ratios between 400 and 500 can indicate presence of sewage.*

MBAS:

Methylene blue active substances (MBAS) analyses are good indicators for the presence of detergents in groundwater and, therefore, of contamination from leaking sewer lines (Phillips et al. 1993). Absence or low concentrations of MBAS indicate the absence of sewage in groundwater or that detergents have been chemically decomposed and removed (Phillips et al. 1993). The analyses further help to discern whether boron concentrations that are found in groundwater are related to seawater intrusion, sewage contamination, or fertilizers. In addition, they help differentiate between nitrate found in groundwater derived from sewage and that derived from fertilizers.

Only a small number of wells (Appendix A, Table A.4) were sampled for MBAS by the Westside Basin Partners in May of 2000. At all of them MBAS was not detected. The absence of MBAS together with the low chloride-to-boron ratios for Arboretum 5, Elk Glenn 2 and Edgewood School indicate that the elevated nitrate concentrations found in these wells (see nitrate discussion below) are not due to leaking sewer lines but most likely due to irrigation return flow containing fertilizers. All of these wells are located in areas where a lot of irrigation occurs (Golden Gate Park and Stern Grove Park). This agrees with observations made by Phillips et al. (1993).

Potassium:

Potassium is generally found in seawater at concentrations of 392 mg/L (Turekian 1968). It can, therefore, also be used as an indicator for potential seawater intrusion. However, like bromide and sodium, potassium is not a conservative constituent in groundwater owing to the fact that it undergoes cation exchange on clay mineral surfaces (Yates et al. 1990). In addition, potassium can be added to groundwater by leaking sewer lines (Yates et al. 1990). Baert et al. (1998) demonstrated that concentrations of 12 mg/L and higher in surface water catchment areas in Flanders were a direct result of surface input. Yates et al. (1990) pointed out that groundwater in the Golden Gate Park and Lake Merced areas (which are not underlain by sewer lines) showed notably lower potassium concentration than adjacent urbanized areas. Water samples collected by the Westside Basin Partners (San Mateo County Environmental Health Division 2001a, 2001b, 2002a) contained low potassium concentrations. However, concentrations at LMMW2S, LMMW2D, LMMW6D and Oceanside wells showed concentrations higher than 10 mg/L (Figure 3.7 and Appendix A, Table A.5). Despite this fact, a clear connection to possible sewage water cannot be confirmed.

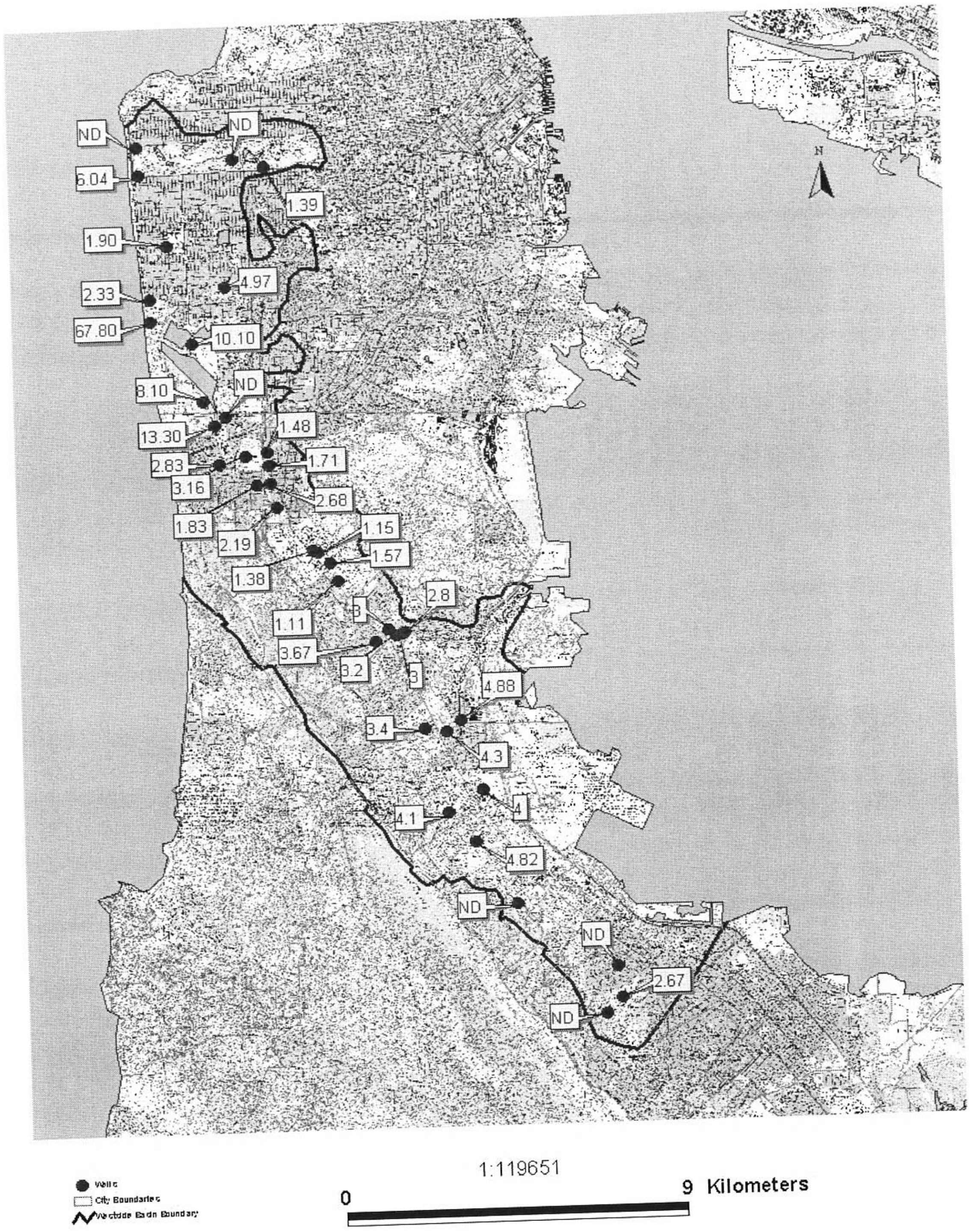


Figure 3.7a: *Potassium concentrations for wells sampled by Westside Basin Partners in May 2000. Since there is no differentiation between wells drawing from different water bearing zones no potassium concentration contours have been interpolated. Source: San Mateo County Environmental Health (2001a).*

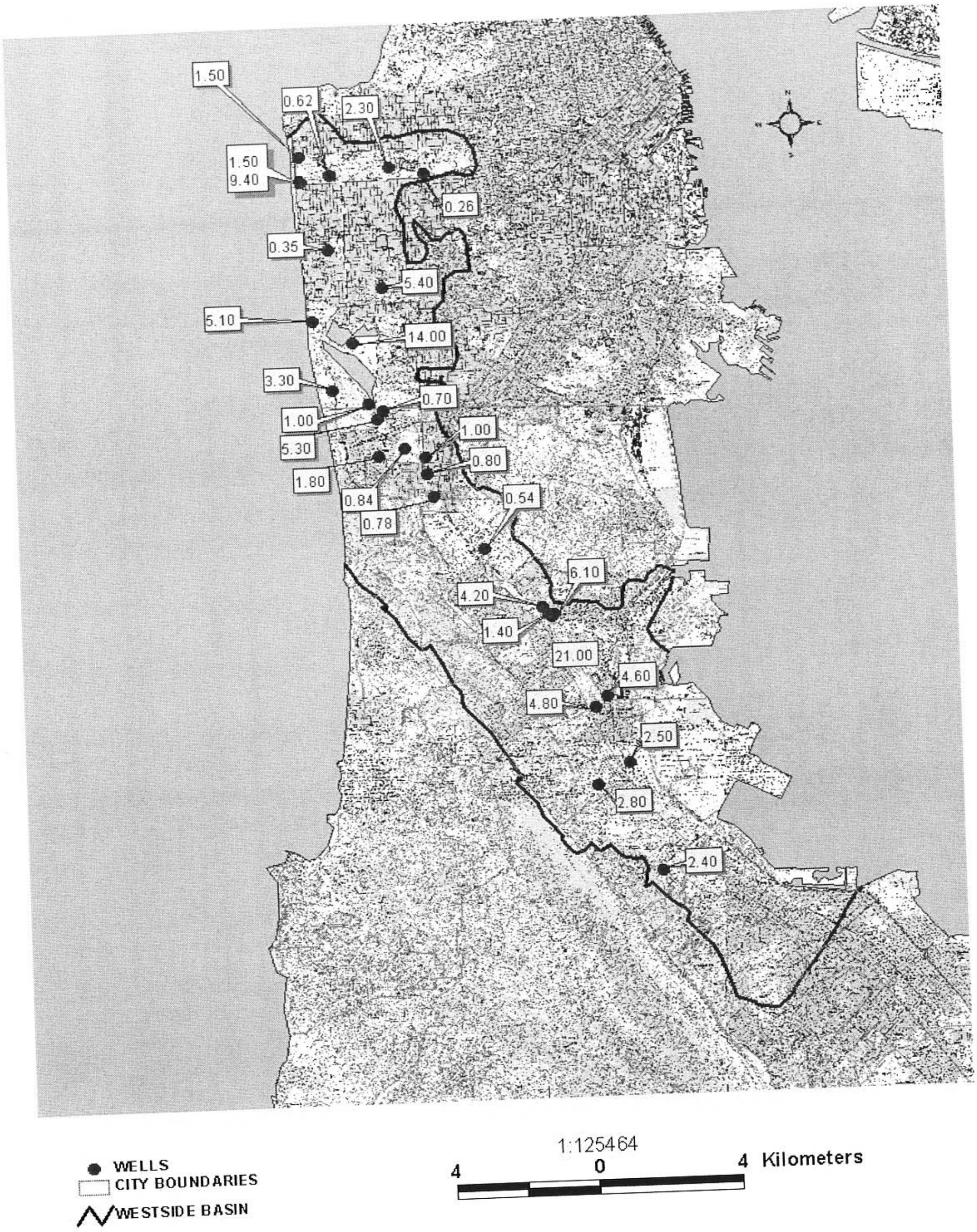


Figure 3.7b: *Potassium concentrations for wells sampled by Westside Basin Partners in April 2001. Since there is no differentiation between wells drawing from different water bearing zones no potassium concentration contours have been interpolated. Source: San Mateo County Environmental Health (2002a).*

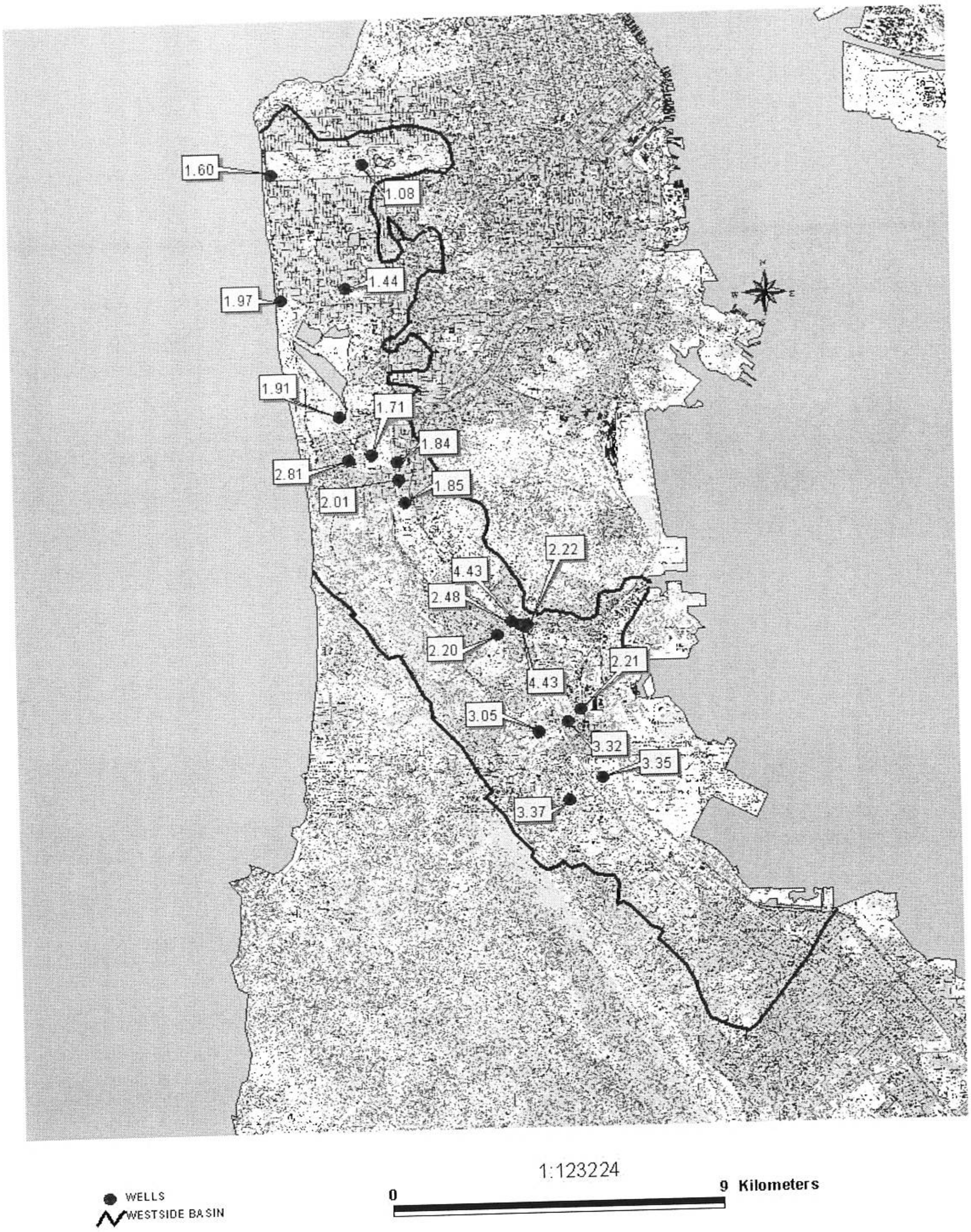


Figure 3.7c: *Potassium concentrations for wells sampled by Westside Basin Partners in October 2001. Since there is no differentiation between wells drawing from different water bearing zones no potassium concentration contours have been interpolated. Source: San Mateo County Environmental Health (2002c).*

Phosphate:

Phosphate is a minor constituent in groundwater and generally occurs only in very small quantities (Spellman and Drinan 2000); however, it can be introduced to groundwater through leaking sewer lines and agricultural runoff. Phosphate is generally attenuated in the vadose zone where it is sorbed to solids, especially metal oxides with positively charged surface sites (Kehew, 2000); it can also form precipitates such as vivianite [$Fe_3(PO_4)_2 \cdot 8H_2O$], strengite [$FePO_4 \cdot 2H_2O$], and variscite [$AlPO_4 \cdot 2H_2O$] (Roberts et al. 1998). Phosphate concentration and distribution in groundwater is pH dependent. Its solubility increases with elevated pH values (Kehew, 2000). Therefore, phosphate concentrations tend to be higher in carbonate rich waters, where pH has moderate values (Kehew 2000). The main problem associated with phosphate is that an increase in phosphate concentrations even as small as 0.01 mg/L can cause serious changes in aquatic life by promoting accelerated plant growth (Spellman and Drinan 2000).

Despite the sorption effects in the vadose zone, phosphate can remain mobile in groundwater and detectable a good distance from the input source. Robertson et al. (1998) reported average phosphate concentrations ranging from 0.03 to 4.9 mg/L at distances up to 70 meters from septic systems in Ontario. In the Westside Basin, samples collected by the Westside Basin Partners (San Mateo County Environmental Health Division, 2001a, 2002a, 2002c) showed concentrations below 0.4 mg/L, even for wells that showed elevated pH values (Figure 3.8 and Appendix A, Table A.5). No specific

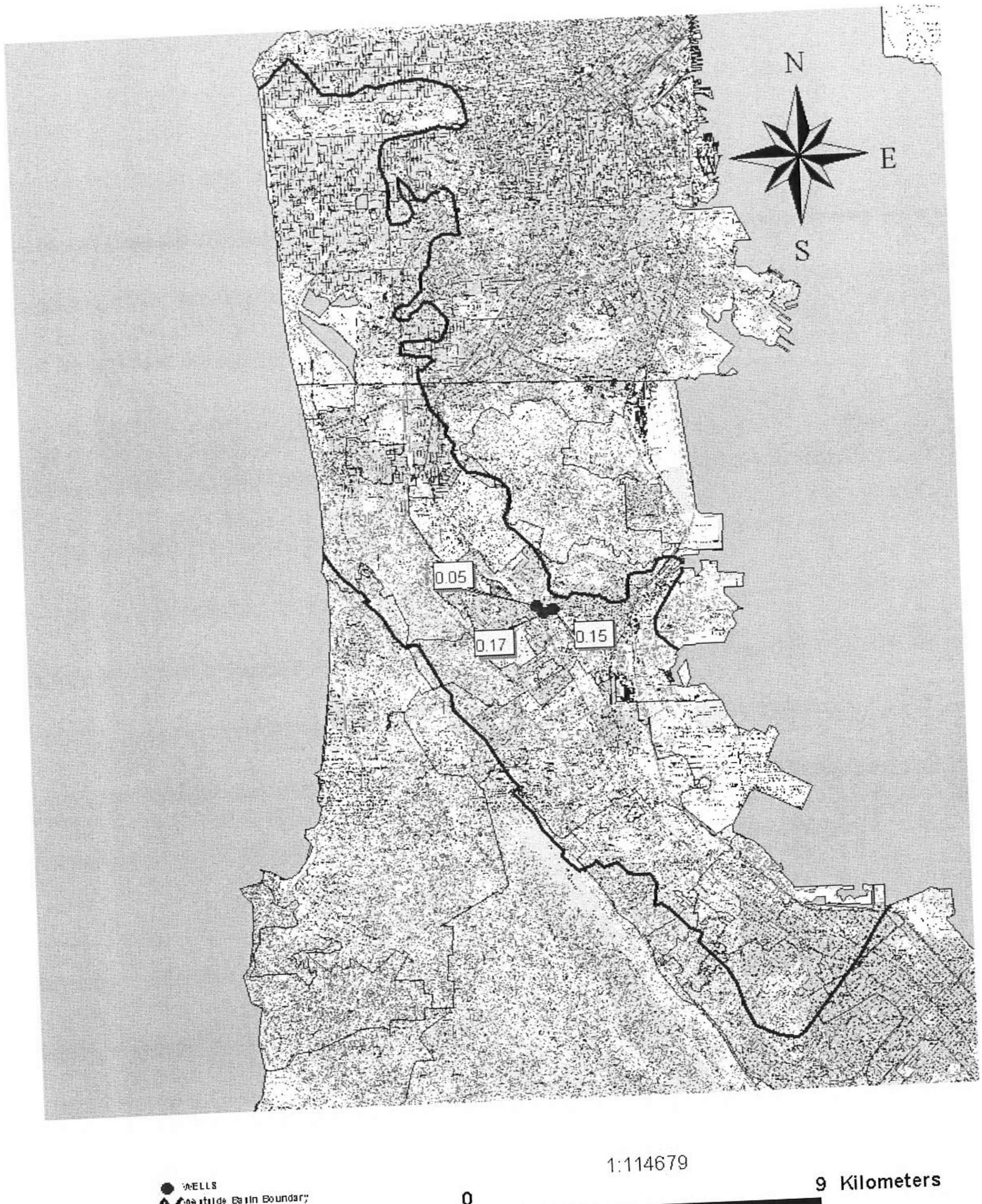


Figure 3.8a: *Phosphate concentrations for wells sampled by Westside Basin Partners in April 2000. Since there is no differentiation between wells drawing from different water bearing zones no potassium concentration contours have been interpolated. Source: San Mateo County Environmental Health (2001a).*

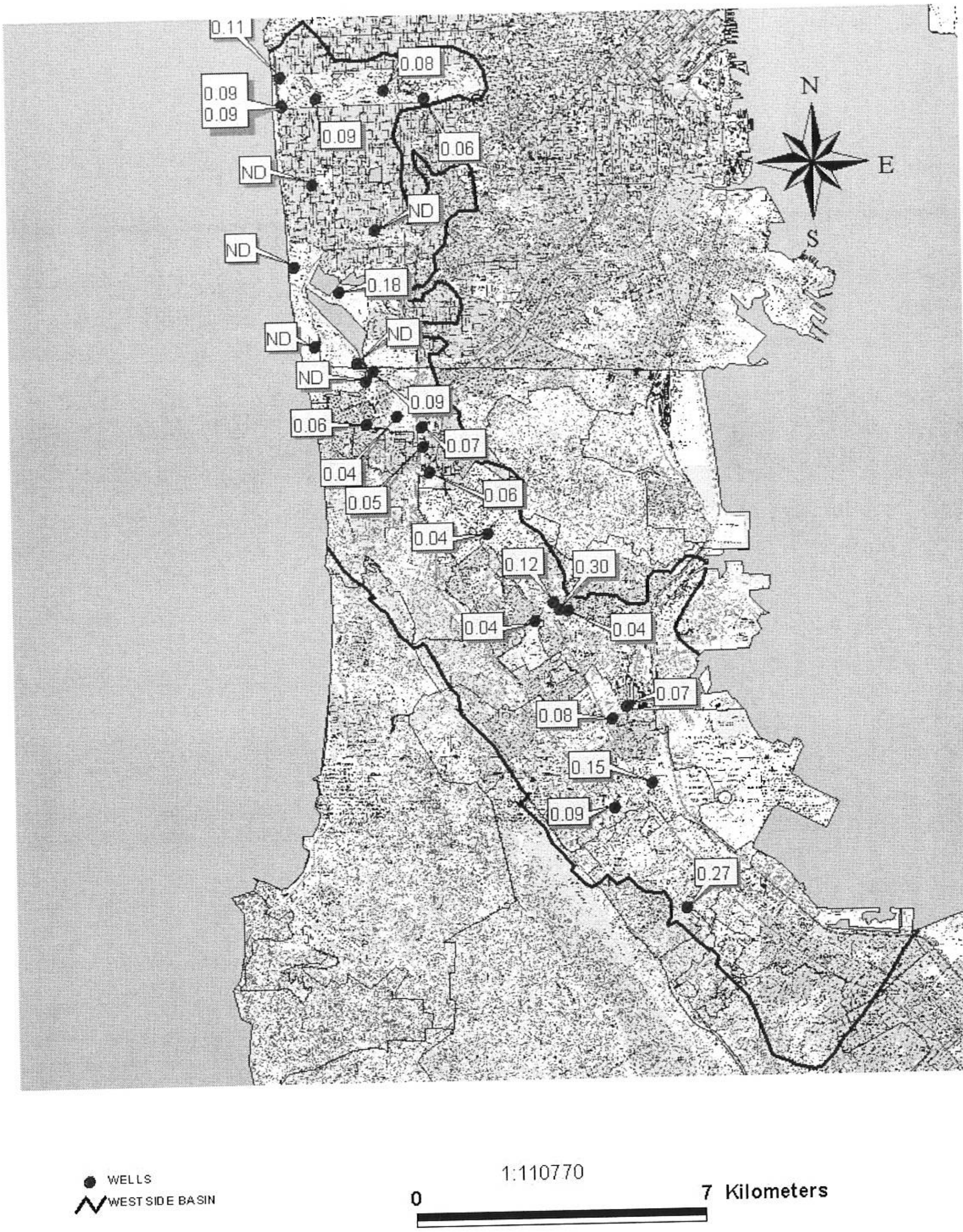


Figure 3.8b: *Phosphate concentrations for wells sampled by Westside Basin Partners in April 2001. Since there is no differentiation between wells drawing from different water bearing zones no potassium concentration contours have been interpolated. Source: San Mateo County Environmental Health (2002a).*

correlation could be observed between carbonate or bicarbonate alkalinity and phosphates. In summary, the concentrations observed in Westside Basin wells in May 2000 and April 2001 do not seem to indicate the presence of sewage in the groundwater.

Sulfate:

Sulfate is also an important constituent of seawater and accounts for about 8% (2,649 mg/L) of its chemical composition (Owens 2002). In general it is a stable ion under oxidizing and alkaline conditions. However, its stability is pH dependent, i.e., as soon as pH is lowered and conditions become reducing to mildly oxidizing sulfate will no longer be stable and will be transformed into dissolved hydrogen sulfide (Yates et al 1990). This factor reduces the reliability of sulfate as an indicator for the presence of seawater intrusion. The pH of seawater (8) is generally higher than of natural groundwater and, therefore, as soon as both start to mix sulfate reduction reactions begin to occur reducing the original proportion of sulfate with other seawater constituents such as chloride (Hem 1985). In addition, cation exchange with fine-grained sediments in the aquifer matrix will also reduce the original sulfate concentration (Phillips et al. 1993). Sulfate can also be introduced to groundwater as a result of human activity. Ammonium sulfate (NH_4SO_4), commonly used as turf fertilizer, can reach groundwater as a result of irrigation-return flow (Yates et al., 1990). Sulfate derived from irrigation-return flow can be identified in groundwater when there is correlation between sulfate and nitrate (Yates et al., 1990).

Chloride-to-sulfate ratios can be used to identify the presence of seawater intrusion in samples (Phillips et al 1993). In seawater the chloride-to-sulfate ration is about 7.17 (Hendrix Group 1998). Figure 3.10 and Table A.7 (Appendix A) show the chloride-to-sulfate ratios of well water samples collected by the Westside Basin Partners (San Mateo County Environmental Health Division 2001a, 2002a, 2002c). Samples collected at LMMW2D and LMMW3D, both located in the deeper water bearing zones around Lake Merced show ratios close to 7.17. High ratio values found in samples collected from the Oceanside well are due to an unusually low sulfate concentration (0.79 mg/L in May 2000 and less than 0.3 mg/L in April 2001). The pH in the well is above 9, which favors the presence of sulfate under stable conditions (Figure 3.9). However, sodium (230 mg/L in April 2001) and carbonate (48 mg/L in April 2001) that are in the Oceanside well are the highest in all of the Westside Basin. Elevated carbonate concentration could be the reason for the high pH in the well water. Such sodium and carbonate concentrations are also associated with a depletion of calcium (Hem 1985). The Oceanside well does show relatively low calcium (10.9 mg/L in May 2000 and 18 mg/L in April 2001). It is feasible that the pH and higher sodium and carbonate concentrations might induce the complexation of calcium with sulfate, therefore, depleting both constituents in the well water.

In general, sulfate concentrations in Westside Basin wells range from 1 to 100 mg/L (San Mateo County Environmental Health Division 2001a, 2002a, 2002c), which is similar to that found by Yates et al (1990) in the western part of San Francisco (2.7 to 72 mg/L). Higher sulfate concentrations are, however, found in two California Water

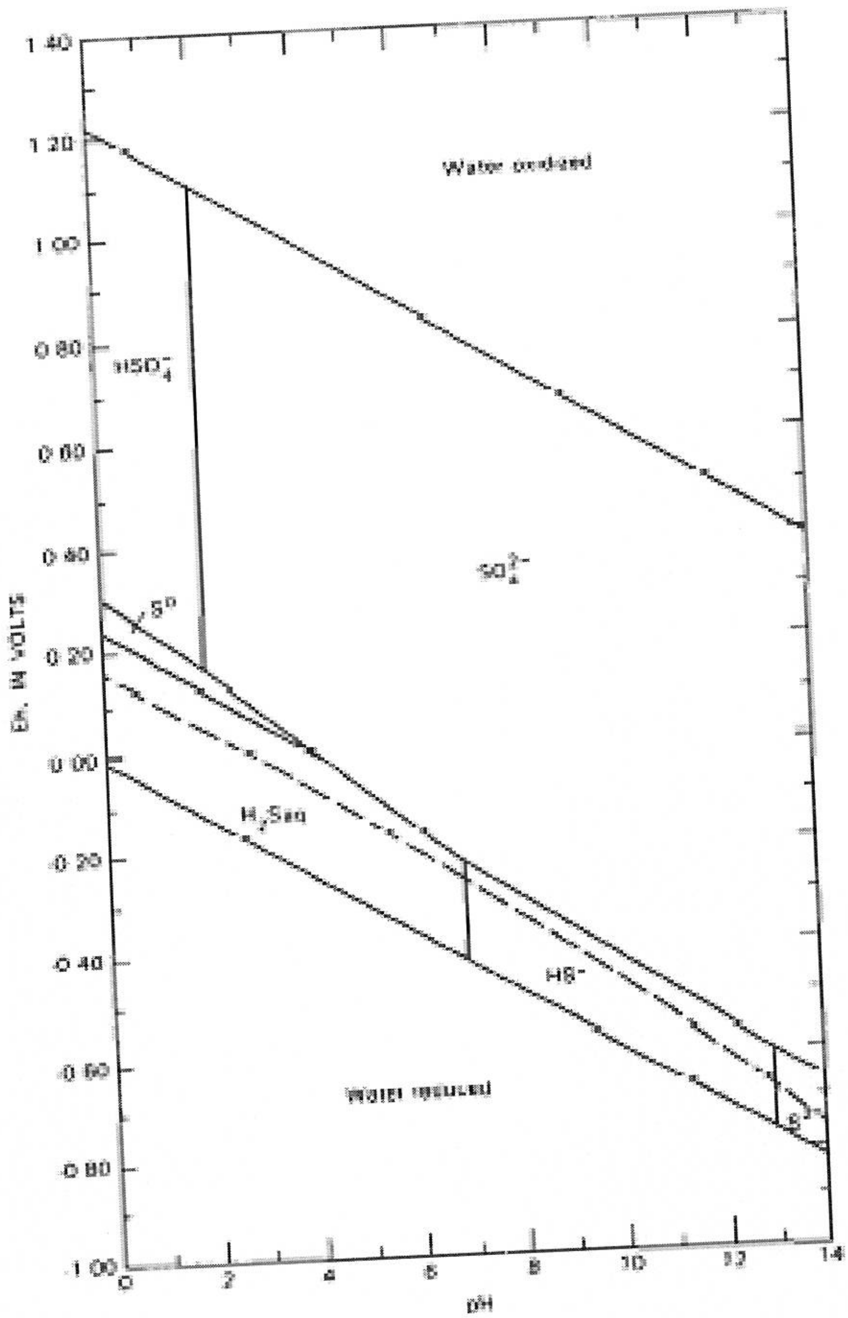


Figure 3.9: *pH and Eh diagram showing the fields of dominance for sulfur species at equilibrium at 25°C and 1 atmosphere pressure. Total dissolved sulfur activity 96-mg/L sulfate. Dashed line represents redox equilibrium between dissolved carbon dioxide species and methane. Source: Hem (1985).*

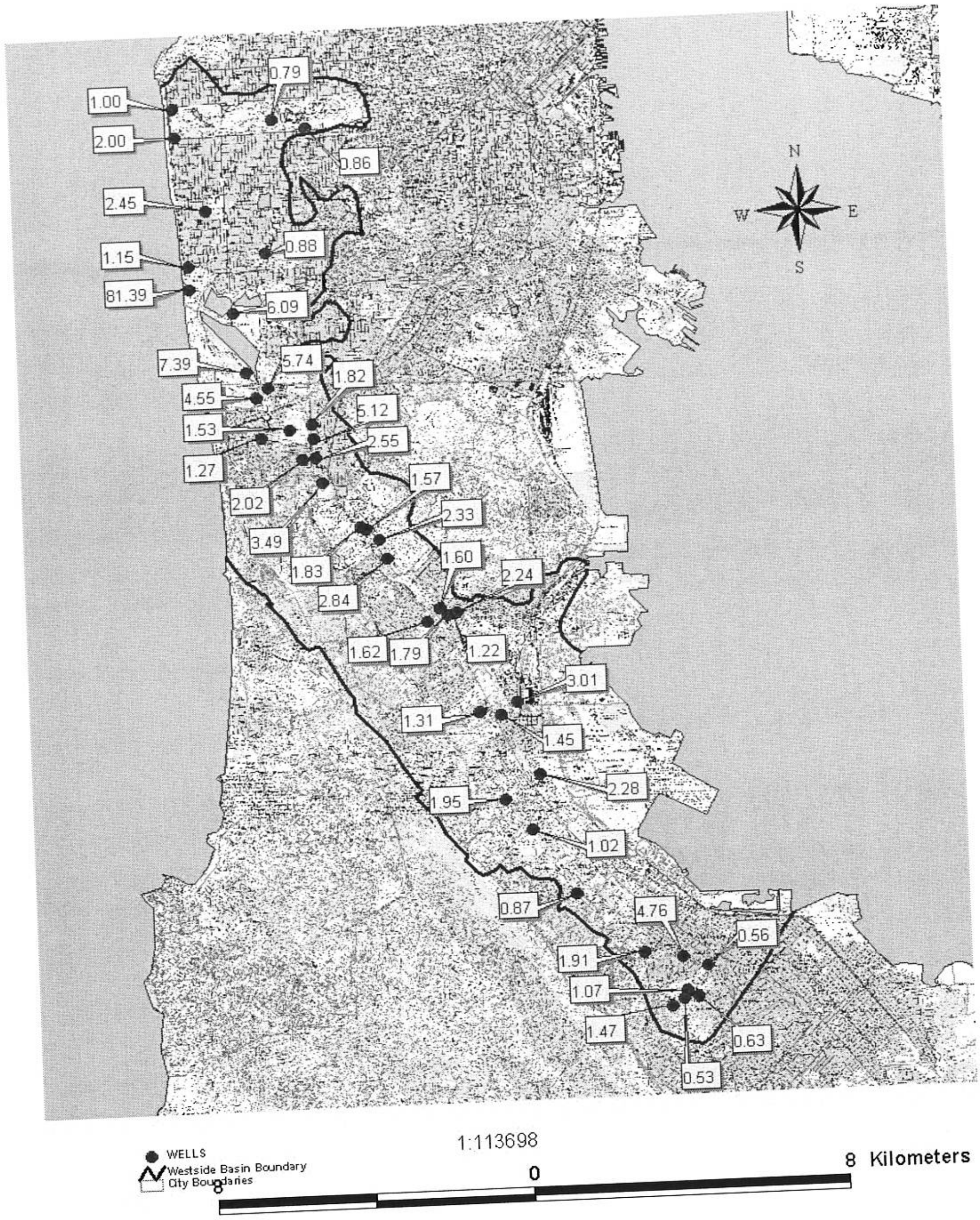


Figure 3.10a:*Chloride-to-sulfate ratios for water sampled collected by the Westside Basin partners in May 2000. In comparison, chloride-to-sulfate ratio of seawater is about 7.00. Of all the collected samples the ratios of LMMW2D and LMMW3D are close to that of seawater. The extremely high chloride-to- sulfate ratio of the Oceanside well is due to an unusually low sulfate concentration in the well water.*

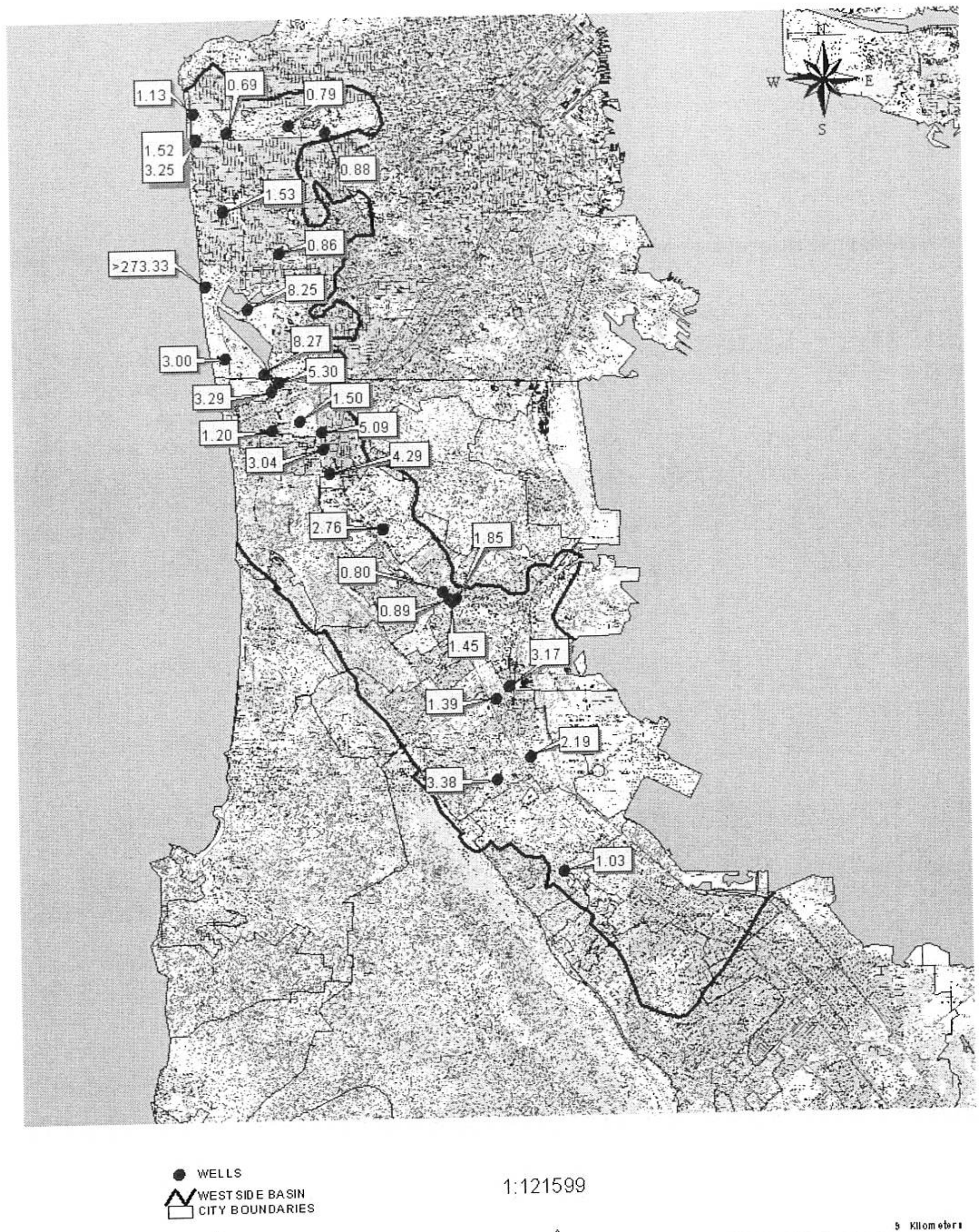


Figure 3.10b:*Chloride-to-sulfate ratios for water sampled collected by the Westside Basin partners in April 2001. In comparison, chloride-to-sulfate ratio of seawater is about 7.00. Of all the collected samples the ratios of LMMW2D and LMMW3D are close to that of seawater. The extremely high chloride-to-sulfate ratio of the Oceanside well is due to an unusually low sulfate concentration in the well water.*

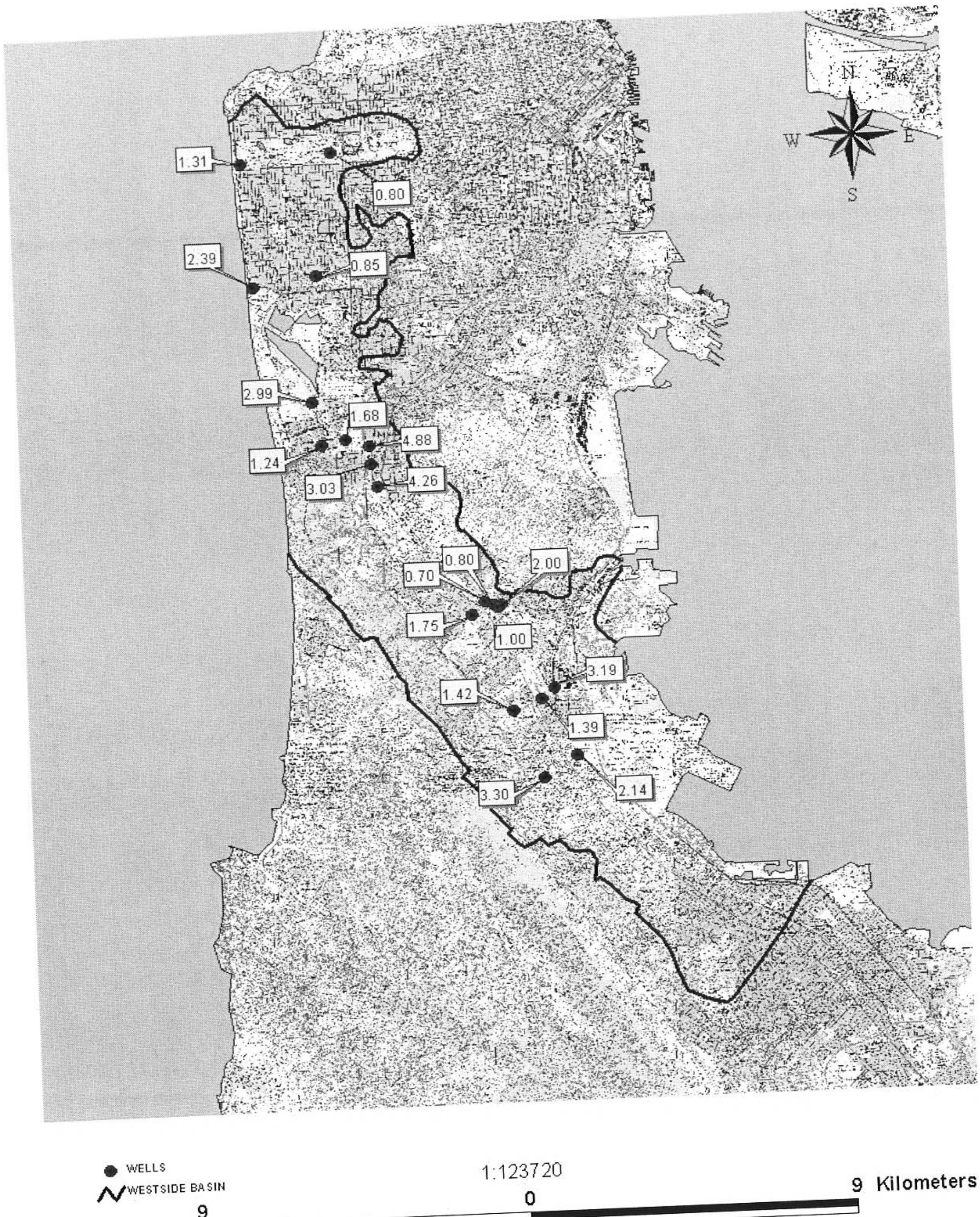


Figure 3.10c:*Chloride-to-sulfate ratios for water sampled collected by the Westside Basin partners in October 2001. In comparison, chloride-to-sulfate ratio of seawater is about 7.00.*

Service wells, SS 1-20 and SS 1-21 (180 to 200 mg/L), both of which have a deeper screening interval than the remaining wells owned by the company.

Nitrate:

Nitrates are a major concern in drinking water due to damaging health effects, especially to infants to whom it can cause methemoglobinemia (Driscoll, 1986). Nitrate concentrations can be analyzed and reported in two ways, either as nitrate measured as nitrogen or nitrate measured as nitrate. Therefore, caution has to be taken when interpreting nitrate values. The U.S. Environmental Protection Agency (1986) set the maximum concentration level (MCL) for nitrate (as nitrogen) at 10 mg/L and for nitrate (as nitrate) at 45 mg/L. These values are exceeded in the Westside Basin and were also noted by Yates et al. (1990) and Phillips et al. (1993). Water samples collected by the Westside Basin Partners in 2000 and 2001 (San Mateo County Environmental Health Division 2001a, 2002a, 2002c), Table A.8 (Appendix A) confirms that observation.

Nitrates can be naturally introduced to the groundwater if peat is present in sedimentary layers. Peat is found in certain sequences of the Merced Formation (Hunter and Clifton 1982) and could explain elevated nitrate concentration, found in some of the deeper wells in the basin like those at the cemeteries in Colma (Home of Peace, Hills of Eternity, Cypress Lawn and Holy Cross), and the municipal wells owned by Daly City and California Water Service Company (A Street, SS 1-14, SS 1-17, SS 1-18 and SS 1-19).

Another natural source of nitrates in groundwater is bulk precipitation, sorption and decomposition of guano (Yates et al. 1990). Yates et al. (1990) determined that assuming that 70% of the 546 mm of average annual precipitation in San Francisco dissolved nitrates from guano would add up to about 6 mg/L nitrate (as nitrogen) in groundwater.

Nitrate concentrations found in many wells in the Westside Basin are higher than background values. Therefore, human activity is likely the source of most of the nitrate in the basin. Major sources of nitrate from human activity are leaking sewer lines, septic tanks and agricultural runoff. Nitrates derived from sewage can be identified if there is a correlation between chloride and nitrates or between potassium and nitrate in water quality data (Yates et al. 1990). Such correlations could not be found in any of the wells analyzed by Yates et al. (1990) in the western part of San Francisco.

Plots of chloride versus nitrate (Figure 3.11) and potassium versus nitrate (Figure 3.13) for samples collected at various wells by the Westside Basin Partners in May 2000 (San Mateo County Environmental Health Division 2001a) do not show a clear correlation between nitrate and either chloride or potassium. Pearson correlation values for nitrate and chloride were determined to further corroborate the diagrams. Samples collected in May 2000, April 2001 and October 2001 have a Pearson correlation values of, respectively, 0.17, -0.05 and –0.26. Overall, these values show that there is no correlation between nitrates and chlorides. However, the Pearson correlation factor for samples collected in October 2001 indicates that a very small inverse relationship between nitrates and chloride might exist. The lack of correlation could be due to independent sources of both chloride and potassium such as connate water and sea spray (Yates et al. 1990). Furthermore, the plots show that for those wells with high nitrate concentration other sources of nitrate are likely to be playing a role, too.

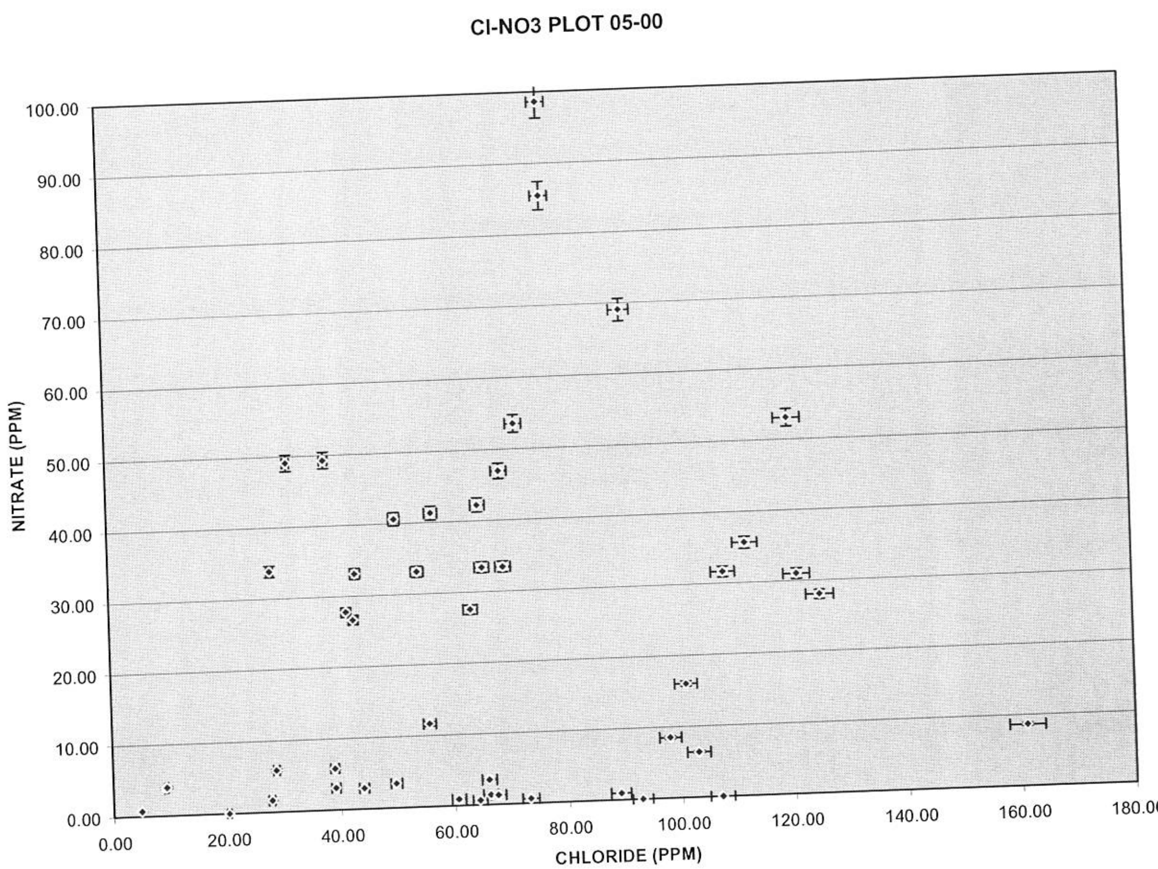


Figure 3.11: *Chloride versus nitrate plot for water samples collected from Westside Basin wells in May 2000 (San Mateo County Environmental Health Division 2001a). Overall no correlation between chloride and nitrate can be observed.*

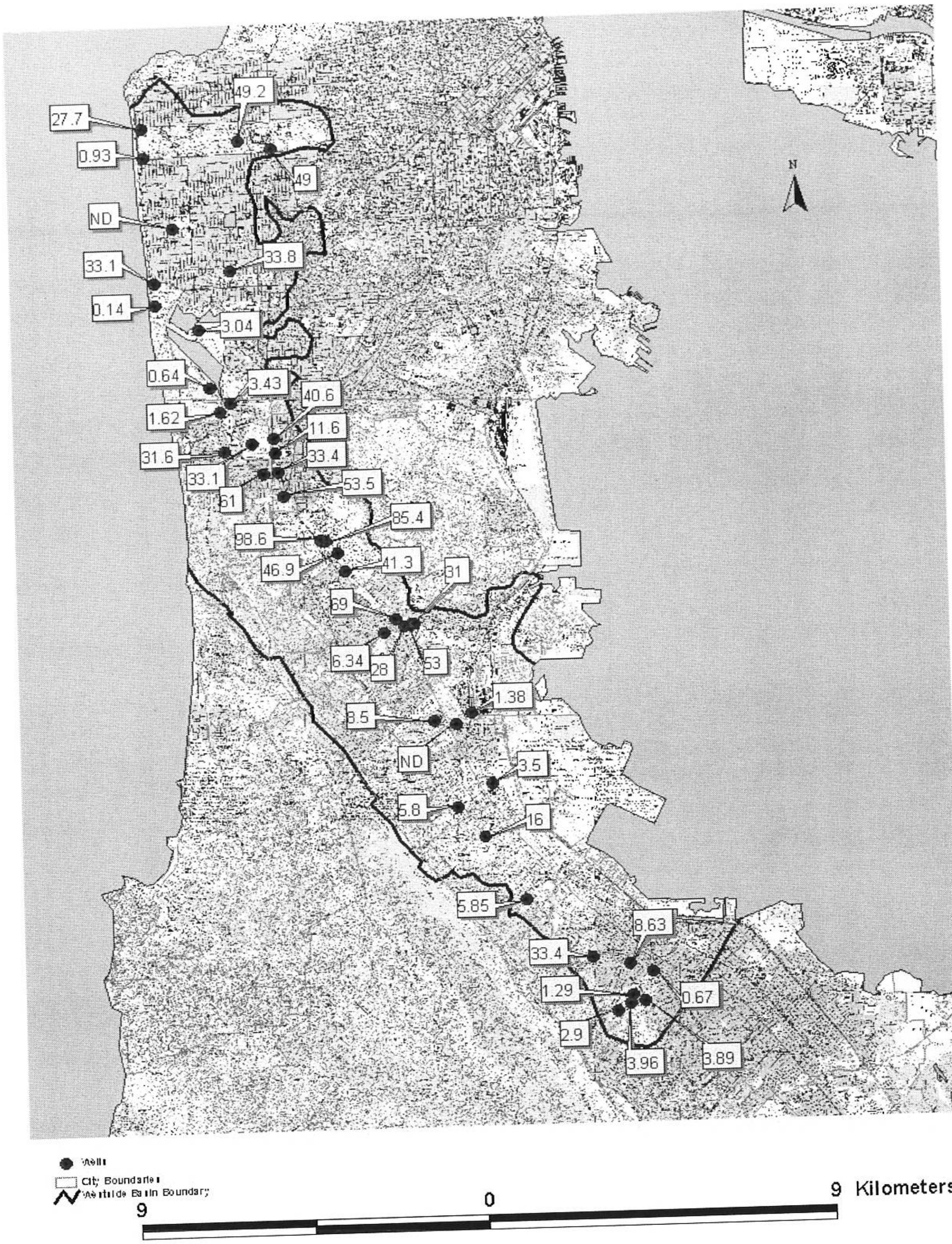


Figure 3.12a: Nitrate values (mg/L) for water sampled collected by the Westside Basin partners in May 2000. Source: San Mateo County Environmental Health (2001a).

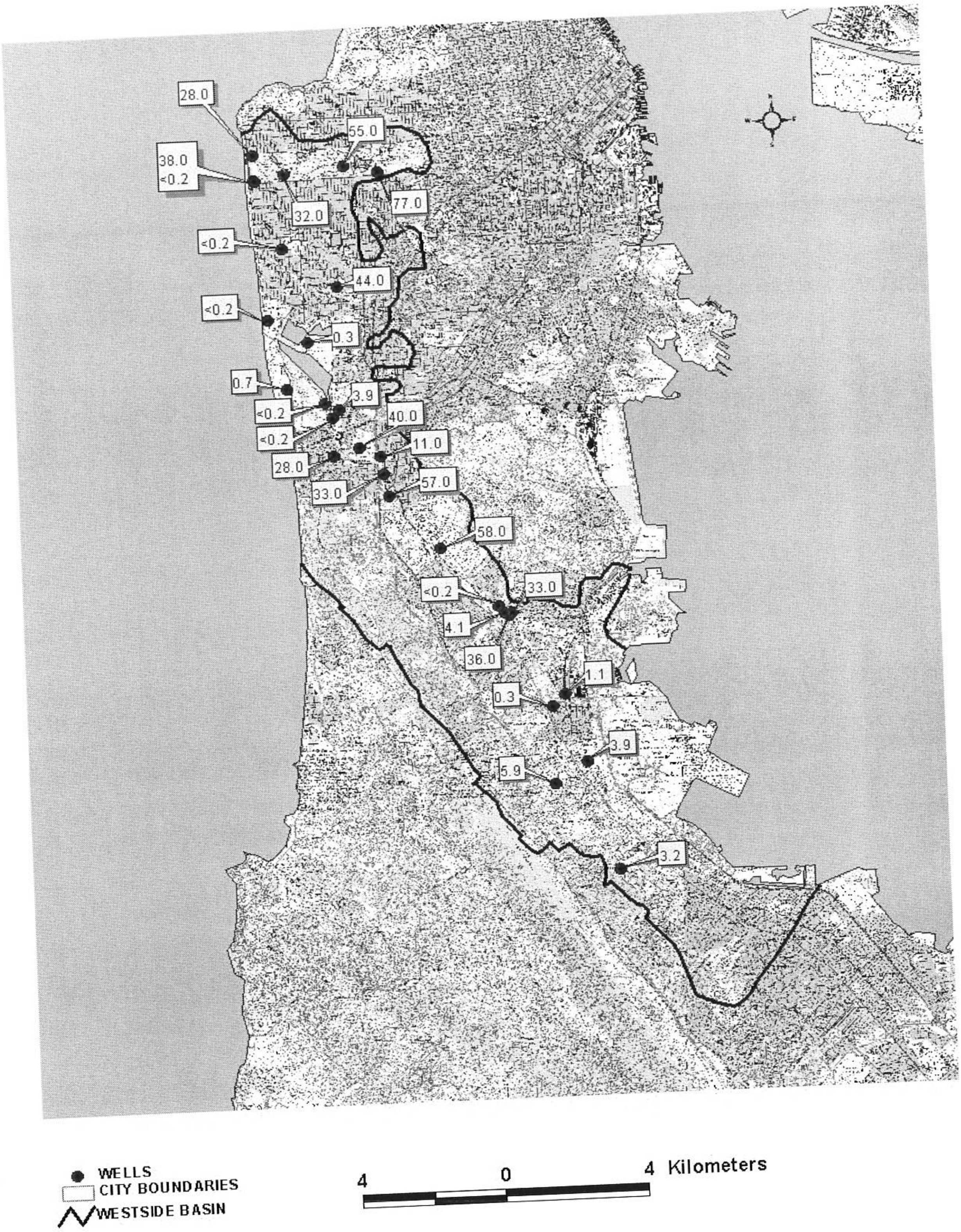


Figure 3.12b: Nitrate values (mg/L) for water sampled collected by the Westside Basin partners in April 2001. Source: San Mateo County Environmental Health (2002a).

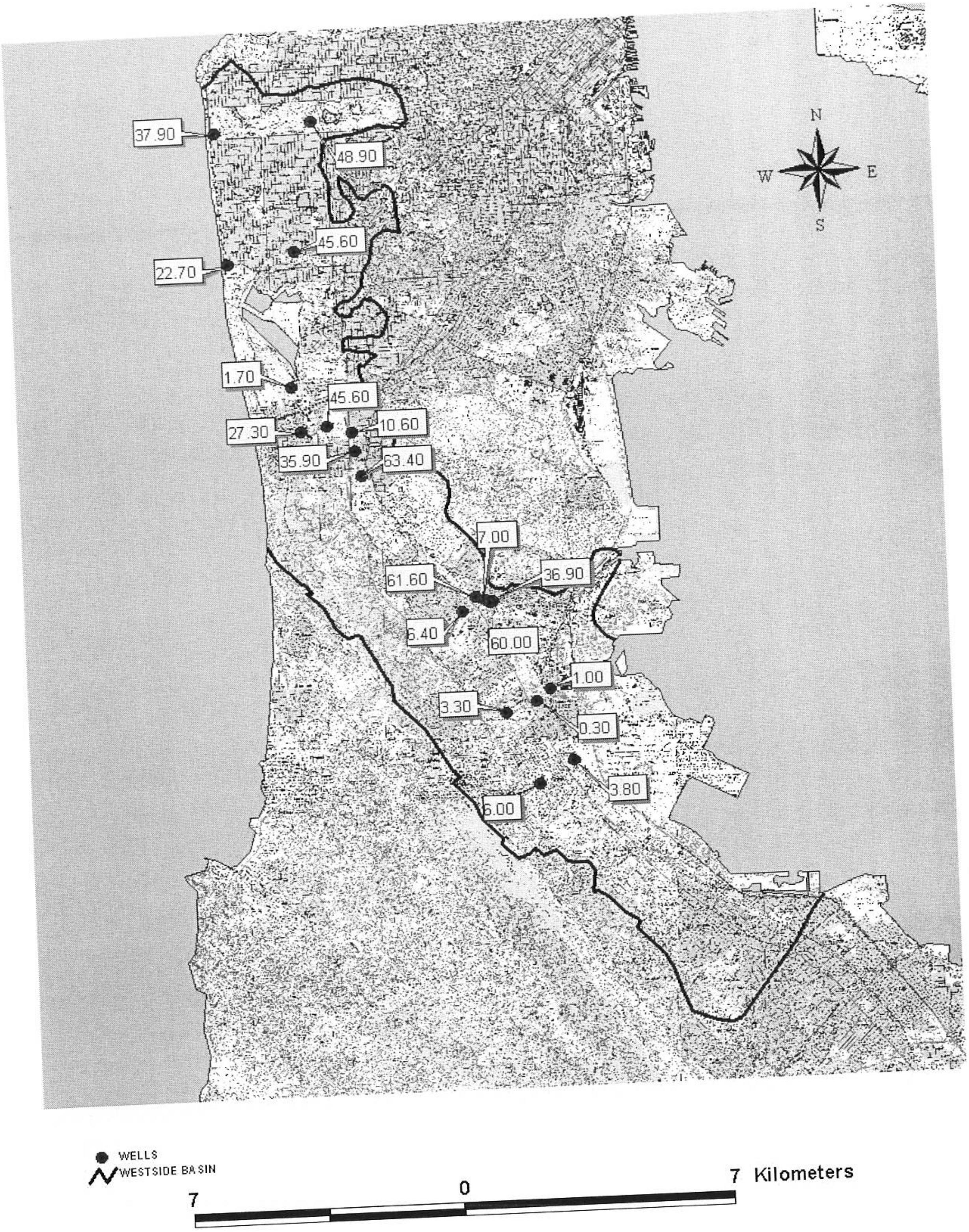


Figure 3.12c: Nitrate values (mg/L) for water sampled collected by the Westside Basin partners in October 2001. Source: San Mateo County Environmental Health (2002c).

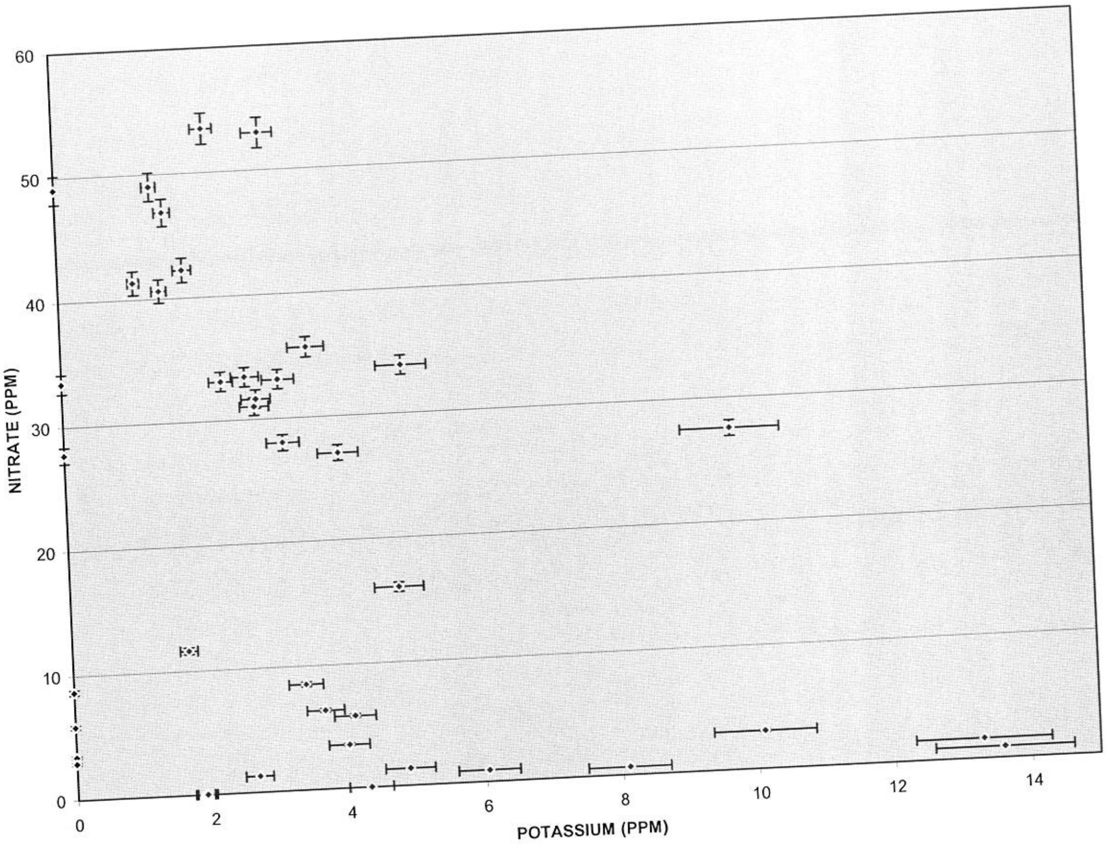


Figure 3.13: *Potassium versus nitrate plot for water samples collected from Westside Basin wells in May 2000 (a). Overall no correlation between potassium and nitrate can be observed.*

Fertilizers can be a major contributor of nitrate. For example, ammonium sulfate (NH_4SO_4) is a commonly used turf fertilizer and could be the source of both nitrate and sulfate in groundwater (Yates et al. 1990). Nitrate from this source can be identified by looking at the correlation between sulfate and nitrate. Yates et al. (1990) as well as Phillips et al. (1993) identified such a correlation at wells in the Golden Gate Park and Lake Merced area. However, such a correlation (Figure 3.14) has not been clear from samples collected at various wells throughout the basin by the Westside Basin Partners in May 2000 (San Mateo County Environmental Health Division 2001a). Nevertheless, higher sulfate concentrations do indicate the presence of irrigation return water in some wells. Most likely the nitrate values derived from irrigation return is being masked by nitrate derived from sewage or from natural sources.

Overall, nitrate concentrations seem to decrease with depth (Yates et al. 1990). This trend is observed at wells with different screen intervals that are located close to each other, e.g. those owned by California Water Service Company in South San Francisco (SS 1-14, SS 1-15, SS 1-17, SS 1-18, SS 1-19, SS 1-20, SS 1-21). Wells SS 1-20 and SS 1-21, which are screened deeper than the remaining California Water Service Company wells do show significantly lower nitrate values (Table A.8, Appendix A). This observation indicates that groundwater composition is primarily controlled by geologic factors and less by urban activities (Boone Cook and Associates 1987, Phillips et al. 1993). Confining layers, whether continuous or discontinuous, separate different groundwater bearing zones (Boone Cook and Associates 1987). However, the presence of higher nitrate concentrations in deep wells in Colma could be derived not just from natural sources but also from infiltration of fertilizers. This irrigation return water could have percolated over a very long period of time through confining layers. Isotopic data, discussed below, does suggest that this might be the case.

Another phenomenon in the nitrate concentration values in the Westside Basin is the impact Lake Merced has on the basin. Yates et al. (1990) noticed that nitrate concentrations in well water south of Lake Merced were substantially lower than north of the Lake. Lake Merced is recharged to the north and east by groundwater and recharges the groundwater basin to the south. This flow pattern is consistent with the general groundwater flow in the area (Figure 3.3). Nitrate in the lake's water is consumed by biological processes. These processes reduce high nitrate water percolating into the lake from the north and east to an ambient concentration of 0.1 mg/L nitrate (as nitrogen) (Phillips et al. 1993). The reduced nitrate concentration in wells south of Lake Merced can even be noticed in deep wells (Figure 3.10 and Appendix A, Table A.8) where concentrations are below 4 mg/L nitrate (as nitrate) (LMMW3D, LMMW6D, Fort Funston D, Fort Funston M, Olympic Country Club 8, San Francisco Golf Club 1).

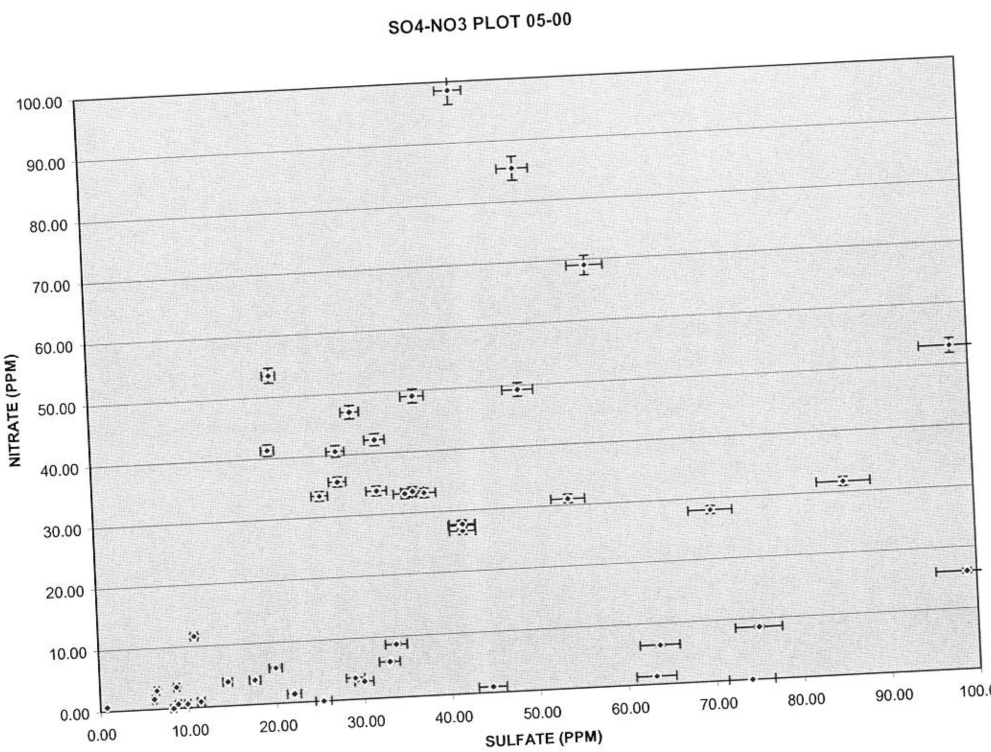


Figure 3.14: *Sulfate versus nitrate plot for water samples collected from Westside Basin wells in May 2000 (a). Overall no clear correlation between sulfate and nitrate can be observed.*

Calcium and Magnesium:

Both calcium and magnesium occur in seawater, however, magnesium occurs in much greater concentration than calcium does. Therefore, low calcium-to-magnesium ratios similar to seawater (0.32) can indicate the presence of saltwater intrusion in a well (Phillips et al. 1993). Nevertheless, these ratios need to be interpreted with caution, owing to the fact that natural groundwater calcium concentrations can undergo cation exchange processes with sodium on the surface of clay minerals, especially montmorillonitic clays. Cation exchange reactions between calcium and sodium in general can decrease the permeability of sediments (Yates et al. 1990). Appendix A, Table A.9 as well as Figure 3.15 show the results of calcium-to-magnesium ratios for wells sampled by the Westside Basin Partners in 2000 and 2001. Except for one sample collected at the Oceanside well none of the samples ratios is close to that of seawater. Therefore, calcium-to-magnesium ratios seem to indicate no overall presence of seawater intrusion in the basin.

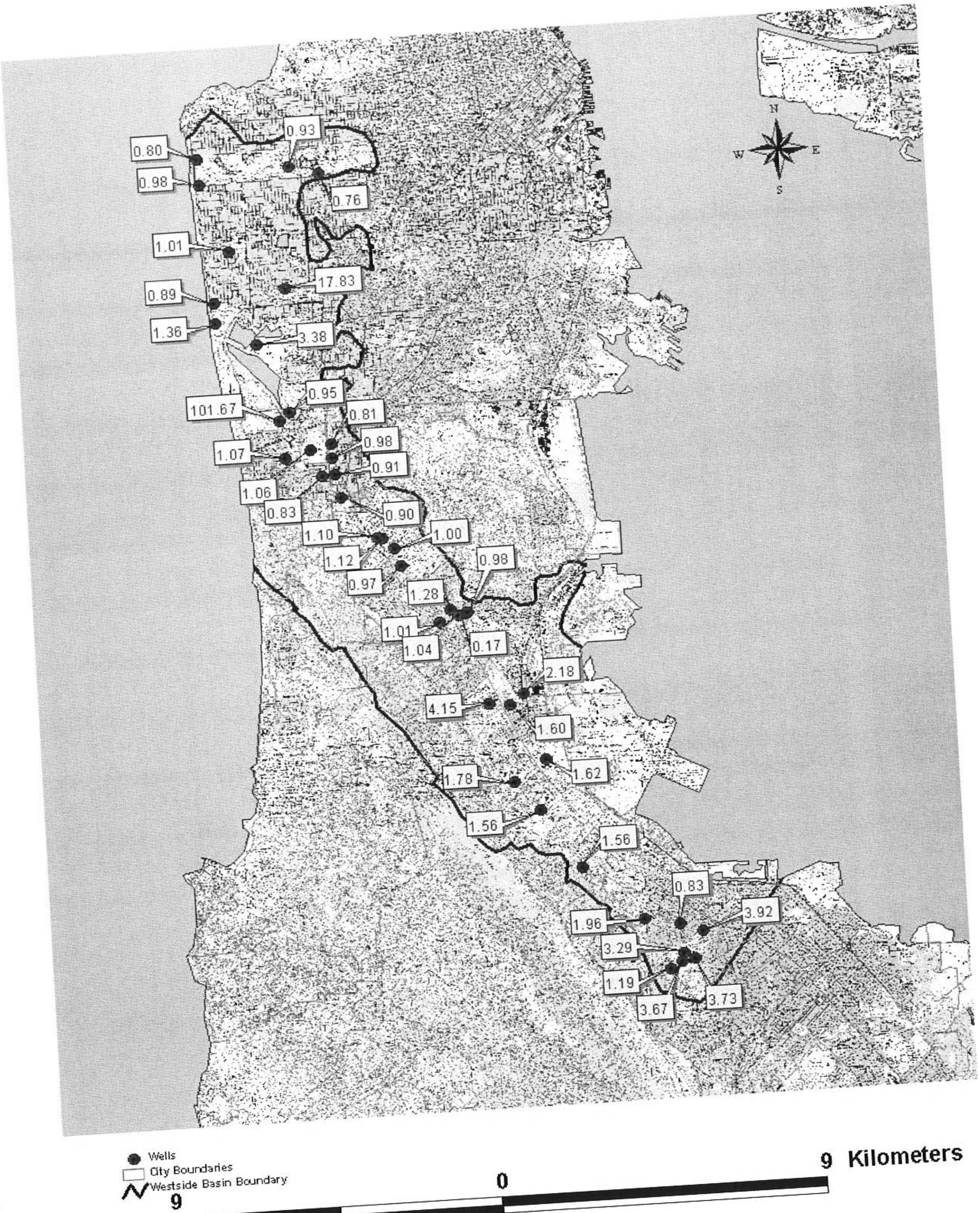


Figure 3.15a:Calcium-to-Magnesium ratios for water sampled collected by the Westside Basin partners in May 2000. In comparison, calcium-to-magnesium ratio of seawater is about 0.32.

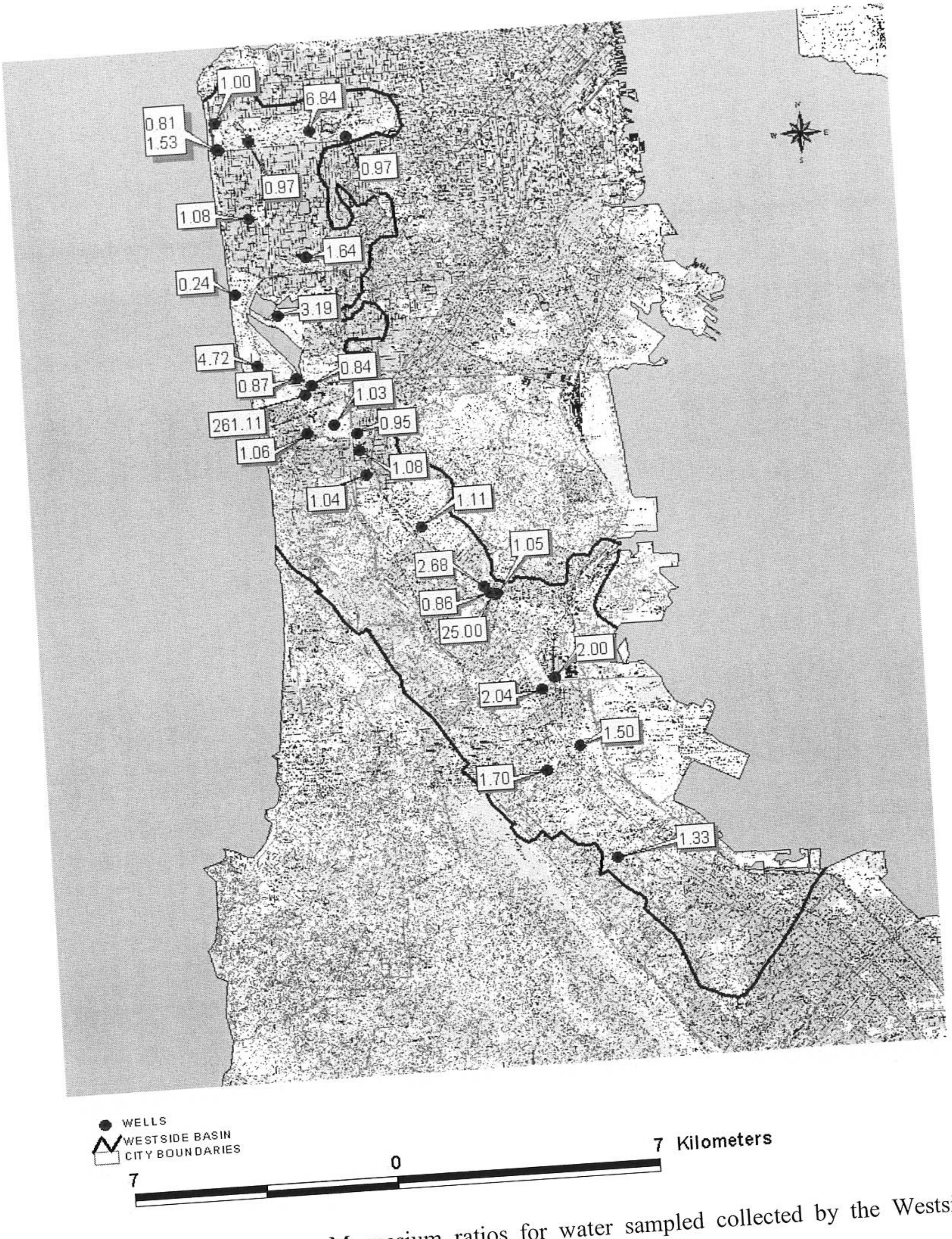


Figure 3.15b:Calcium-to-Magnesium ratios for water sampled collected by the Westside Basin partners in April 2001. In comparison, calcium-to magnesium ratio of seawater is about 0.32.

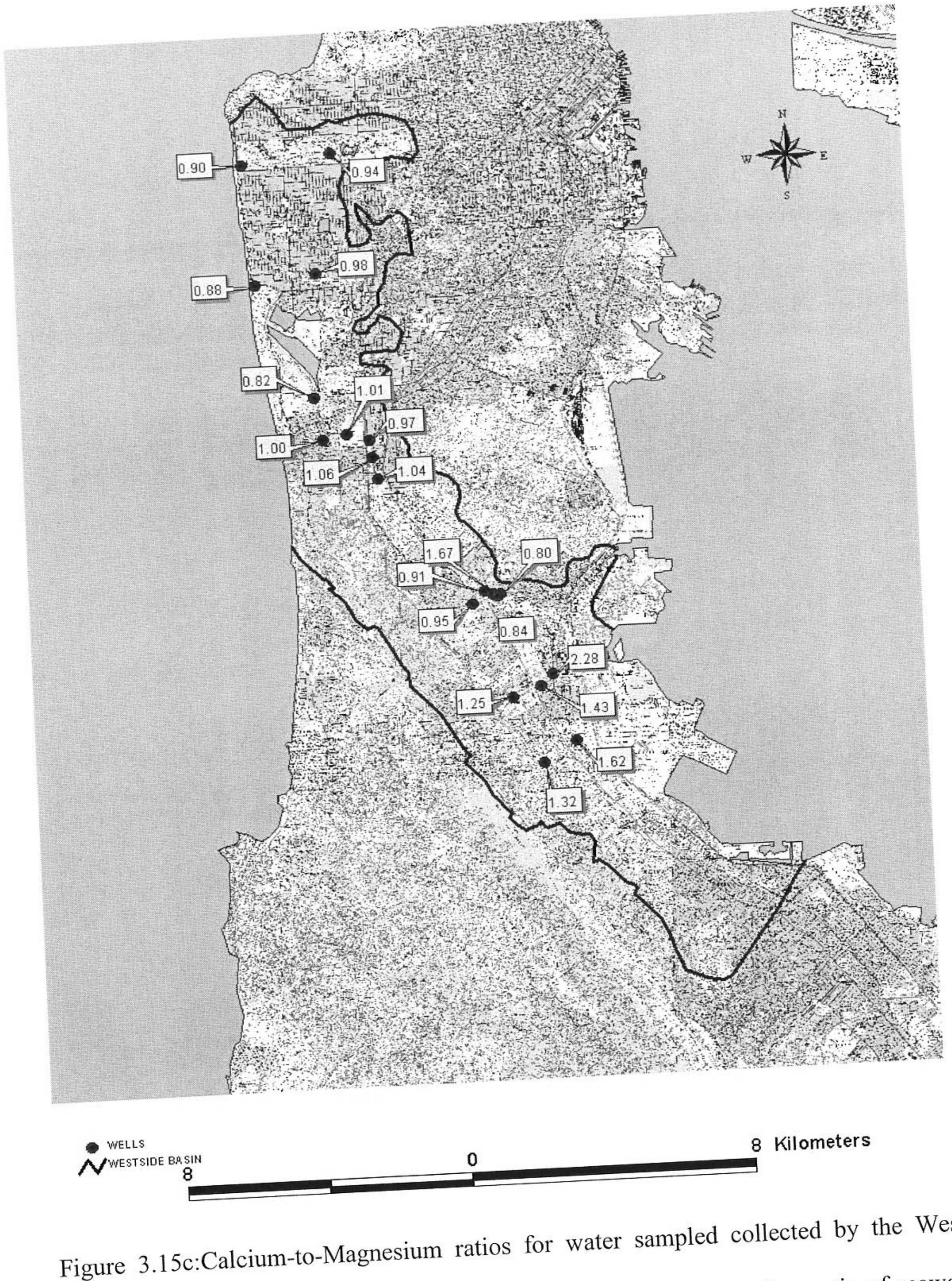


Figure 3.15c:Calcium-to-Magnesium ratios for water sampled collected by the Westside Basin partners in October 2001. In comparison, calcium-to-magnesium ratio of seawater is about 0.32. Source: San Mateo County Environmental Health (2002 c).

Piper and Stiff Diagrams:

The main purpose of a piper diagram is to show clustering of data points to indicate distinct water quality populations (Fetter, 1994). The major ions (calcium, magnesium, sodium, potassium, chloride, sulfate, carbonate and bicarbonate) are plotted as percentages of milli-equivalents in two base triangles (Figure 3.16). The total cations and the total anions are set equal to 100% and the data points in the two triangles are projected onto an adjacent grid. For each individual water sample, a water quality type for the major ions can be assigned based on the location of the sample within the two base triangles. This plot reveals useful properties and relationships for large sample groups.

Piper diagram for samples collected in May 2000 (San Mateo County Environmental Health 2001a) is presented in Figure 3.16. The majority of the sampled wells show no dominant cation (about 76 %). About 50 % of the sampled wells show no dominant anion and 45% bicarbonate as dominant anion; thereby yielding a mixed ion type of water. The most noticeable outliers are the USGS South Windmill D, the Oceanside and LMMW3D wells. A common denominator among these three wells is the presence of ammonia and very small nitrate concentrations compared to other Westside Basin wells. Furthermore, LMMW3D and Oceanside wells show elevated pH levels (11.4 and 9.35, respectively). As a result, the calculated pe values of the LMMW3D and Oceanside wells are very low (-4.21 and –1.86, respectively) (Figure 3.17). Such low pe values are characteristic of reducing environments where biodegradation of organics

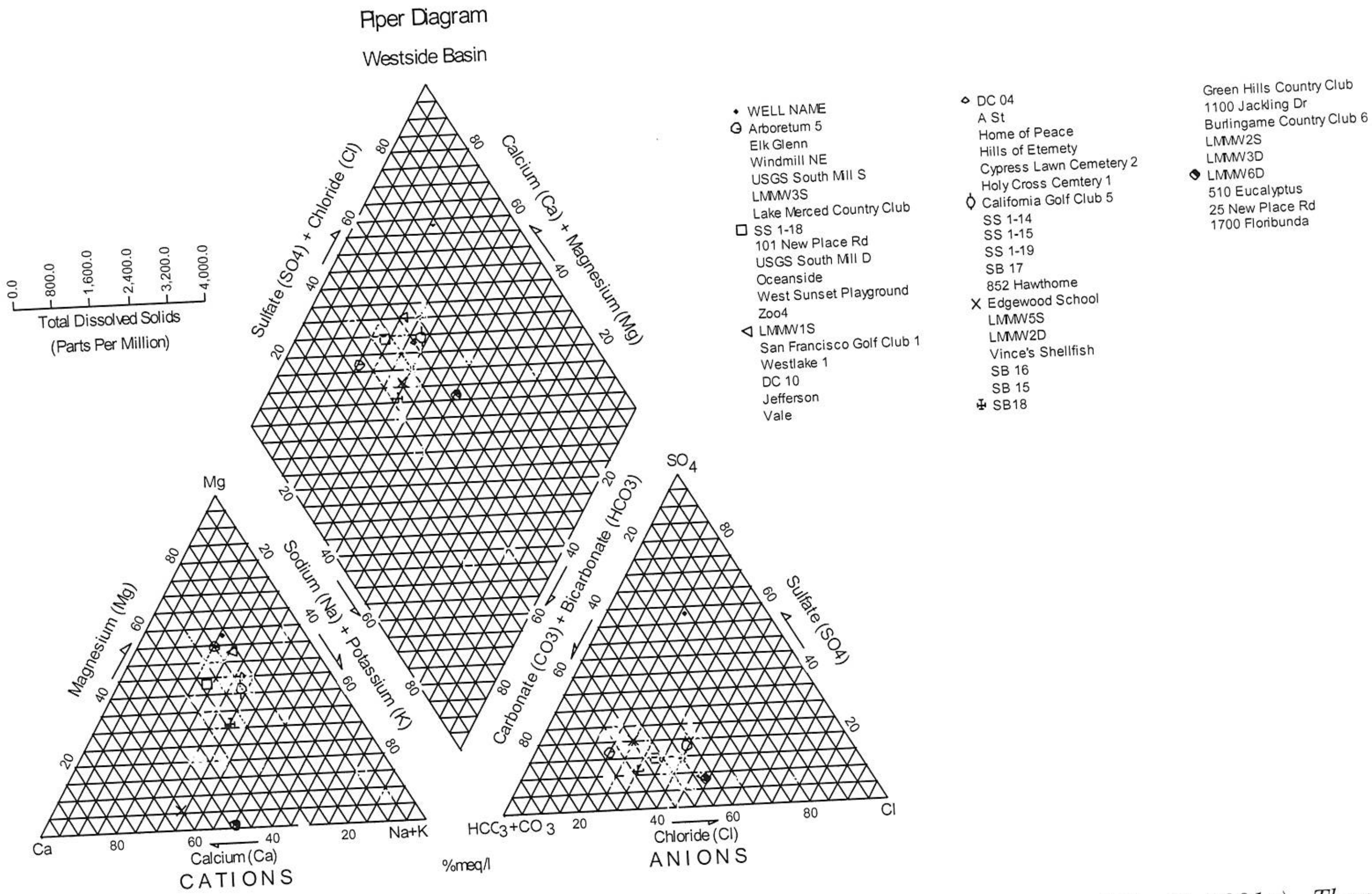


Figure 3.16: *Piper diagram for samples collected in May 2000 (San Mateo County Environmental Health 2001a). The majority of the sampled wells show no dominant cation and bicarbonate as dominant anion.*

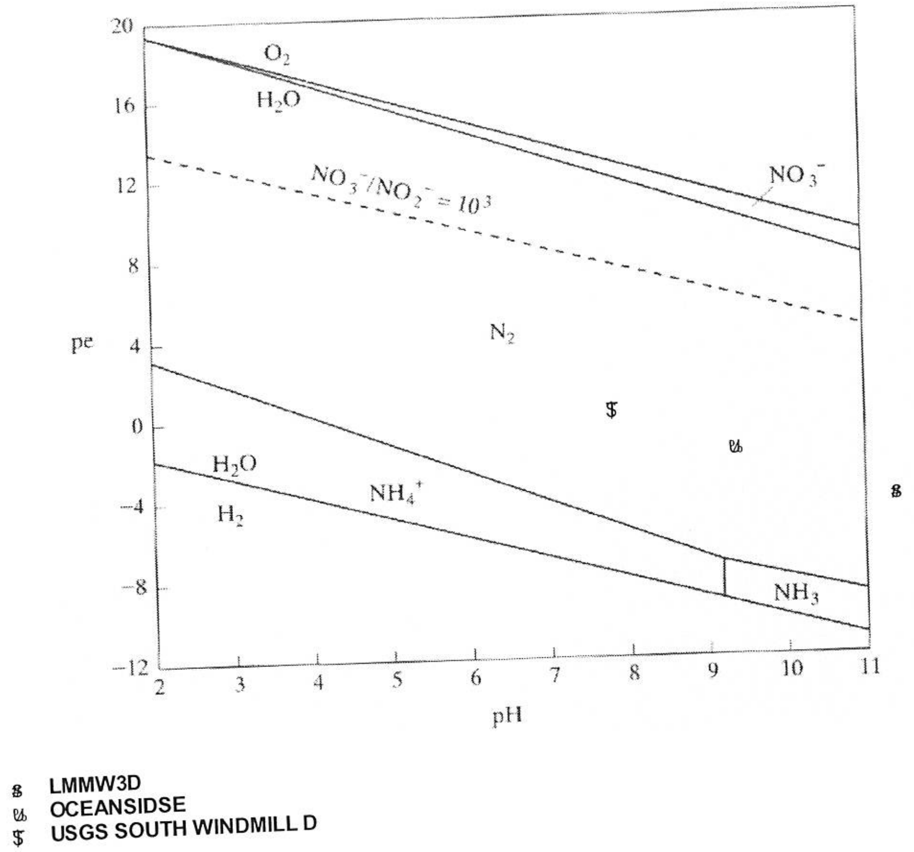


Figure 3.17: *pe-pH diagram for selected species in the system N-O2-H20 at 25 °C. The plotted values are for samples collected at LMMW3D, Oceanside and USGS S Windmill D wells in May 2000.*

compounds is occurring. At the USGS South Windmill well the pH value falls within the range of Westside Basin wells (7.84) and, consequently, the pe value is around zero (0.16).

As shown in Figure 3.18, at high pH values bicarbonate is almost non-existent in solution and is replaced by carbonate. It is feasible that the decomposition of the organic compounds increases the pH value in the wells transforming nitrates into ammonia and the bicarbonates into carbonates.

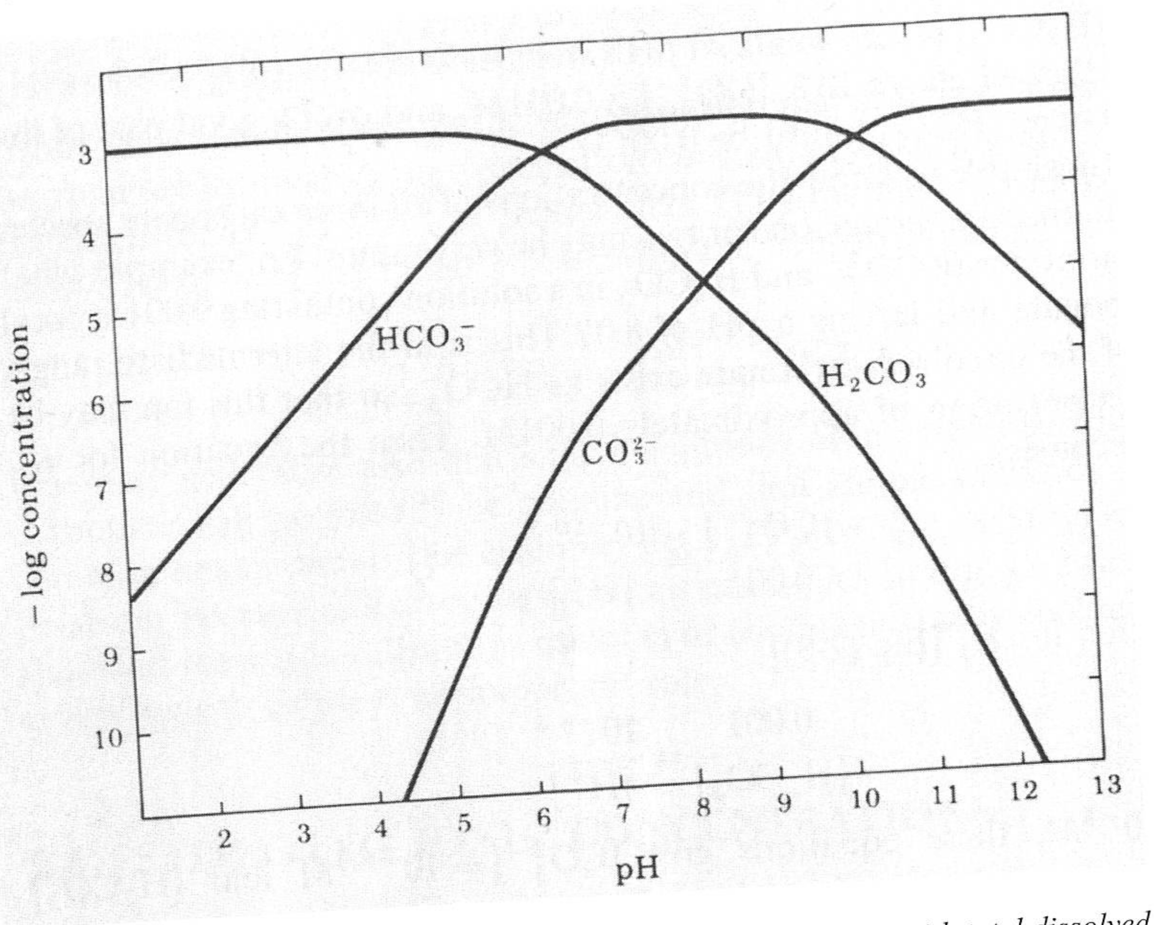


Figure 3.18: *Concentration of carbonate species at 25 ℃, in solution with total dissolved carbonate=0.001M. At higher pH values bicarbonate is replaced by carbonate. Source: Krauskopf (1979).*

A piper diagram for samples collected in April 2001 (San Mateo County Environmental Health 2002a) is presented in Figure 3.19. The majority of the sampled wells show no dominant cation (about 71 %). About 42% of the sampled wells show no dominant anion and 44% bicarbonate as dominant anion; thereby yielding a mixed type of water. The most noticeable outliers are the USGS South Windmill D, Oceanside, LMMW2D, Fort Funston D, Fort Funston M, Fort Funston S, Elk Glenn and SS 1-14 wells. From all of these outliers, only the Oceanside well has a low pe (Figure 3.20). This well has a high pH value (9.3). As in the sample collected at this well in May 2001, possibly the decomposition of organic compounds could be affecting the water chemistry in the well. Organic compounds could also be affecting the chemistry of USGS South Windmill D well. This well has no detectable concentration of nitrates; however small concentrations of ammonia were measured. The majority of the alkalinity is carbonate alkalinity and there is also phenol alkalinity present in the well. Phenol can be found in groundwater as the result of the decomposition of lignite by soil bacteria (basidiomycetes) (Alexander, 1991). At the Elk Glenn, Fort Funston M, Fort Funston S, LMMW2D and SS 1-14 wells the calcium and magnesium concentrations are much lower than the sodium and potassium concentrations. These wells could possibly be screened in clayey layers where cation exchange reactions occur, replacing calcium and magnesium with sodium and potassium. The Fort Funston D well is the deepest well in the Westside Basin. It is screened from 442 to 454 meters below surface. The well log shows the presence of clay rich sediments. It is, therefore, feasible that the low concentration in minerals in the well water is due to sorption on clay mineral surfaces.

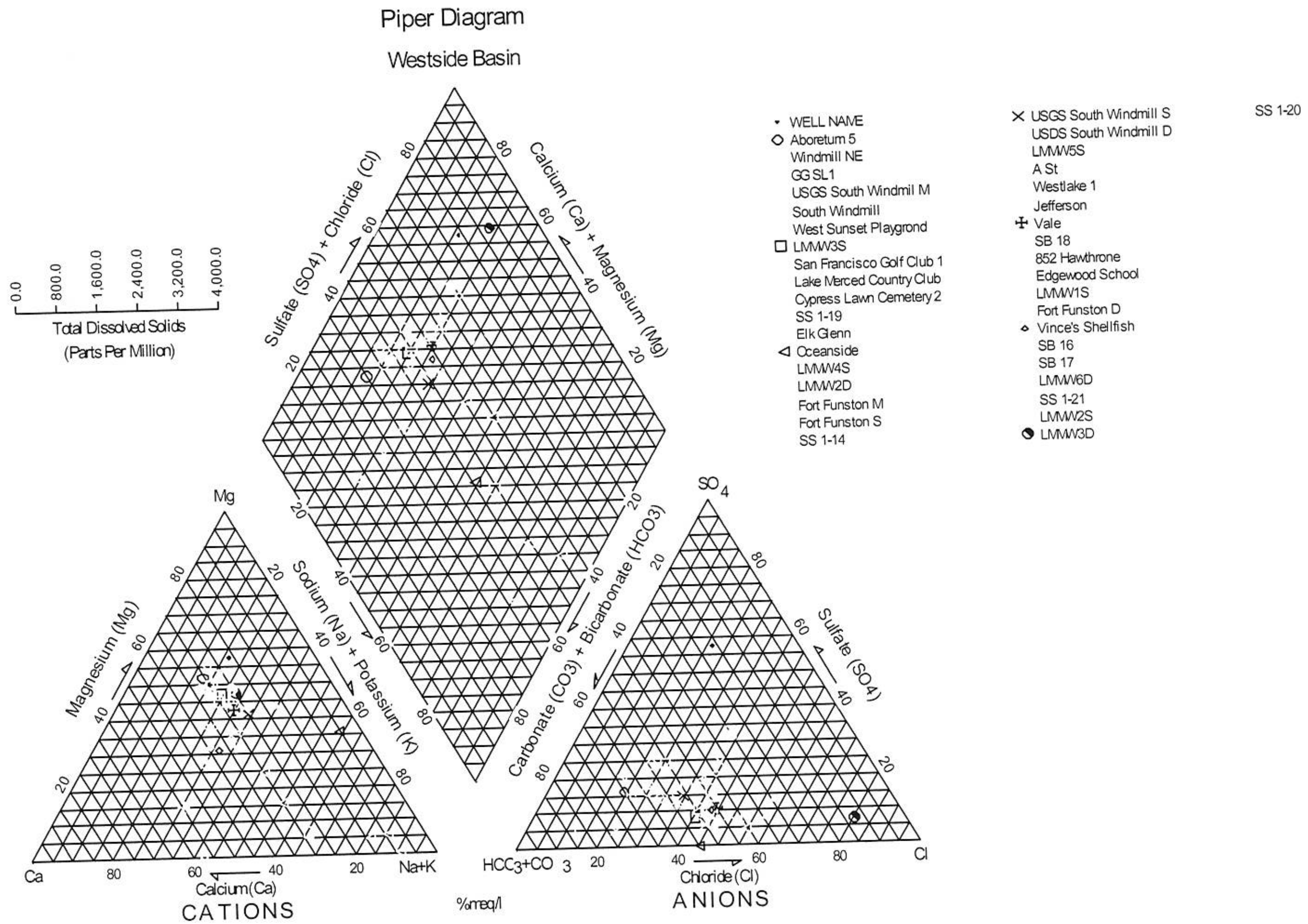


Figure 3.19: *Piper diagram for samples collected in April 2001 (San Mateo County Environmental Health 2002a). The majority of the sampled wells show no dominant cation and bicarbonate as dominant anion.*

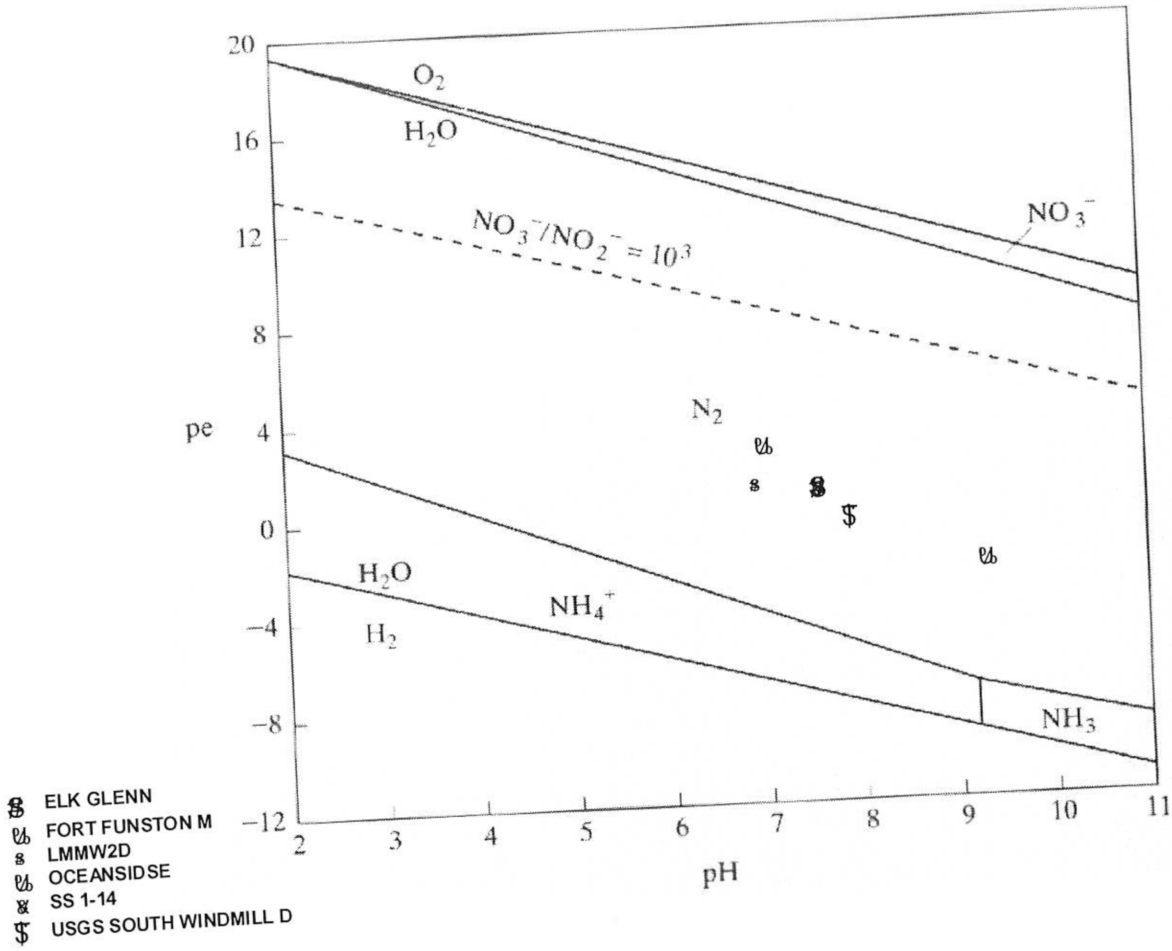


Figure 3.20: *pe-pH diagram for selected species in the system N-O2-H20 at 25℃. The plotted values are for samples collected at LMMW3D, Oceanside and USGS S Windmill D wells in April 2001.*

Piper diagram for samples collected in October 2001 (San Mateo County Environmental Health 2002c) is presented in Figure 3.21. All of the sampled wells showed no dominant cation. About 70 % of the sampled wells show no dominant anion and 30% bicarbonate as dominant anion; thereby yielding a mixed water type. There were no outliers among the sampled wells. Those wells that had been outliers in the two pervious sampling events were not sampled in October 2001.

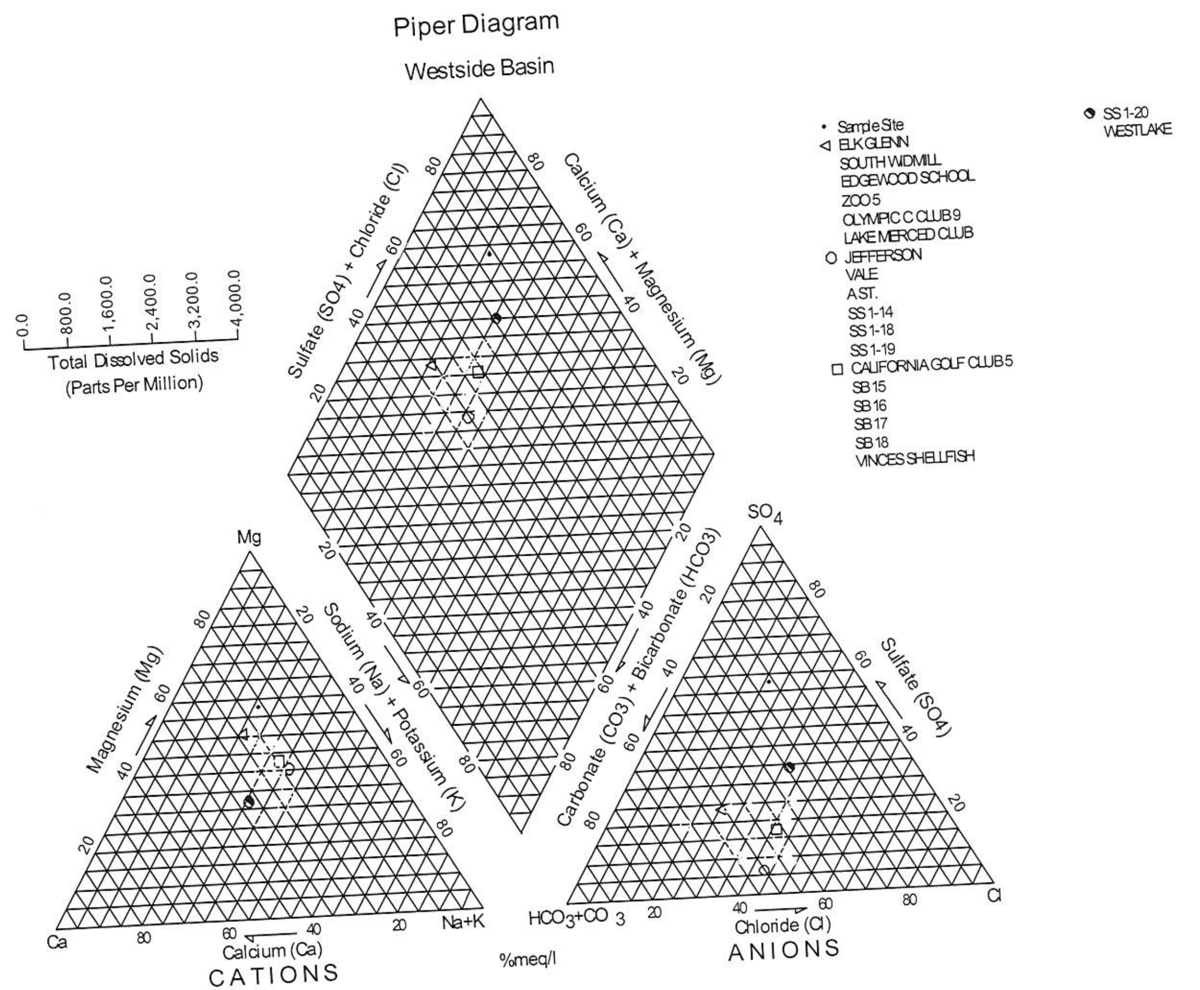


Figure 3.21: *Piper diagram for samples collected in October 2001 (San Mateo County Environmental Health 2002c). The majority of the sampled wells show no dominant cation and bicarbonate as dominant anion.*

Stiff diagrams are developed to allow a graphical comparison between chemical analyses. Water samples collected from different water bearing zones will show different polygonal shapes. The larger the polygons are the larger the concentration of the different ions is. The diagrams are created by extending three horizontal axes in either direction of a vertical zero axis. Sodium, potassium, calcium, magnesium, chloride, bicarbonate and sulfate are plotted in milliequivalents; the cations to the left of the zero axis and the anions to the right.

Stiff diagrams were developed for samples collected in May 2000, April 2001 and October 2001 (Figure 3.22). For each year the diagrams have been organized based on the shape of the diagrams. Various different shapes are present for Westside Basin wells. The grouping of the shapes by their form does not suggest that water quality changes regionally. For a specific shape there are wells from different areas in the basin present. Furthermore, grouping the wells by geographic location throughout the basin shows that for each area there are different shapes present. Some of these differences even occur for wells that located in close proximity to each other. However, in such cases, these wells are screened at different depths. This further corroborates the hypothesis that several water bearing zones are present in the basin.

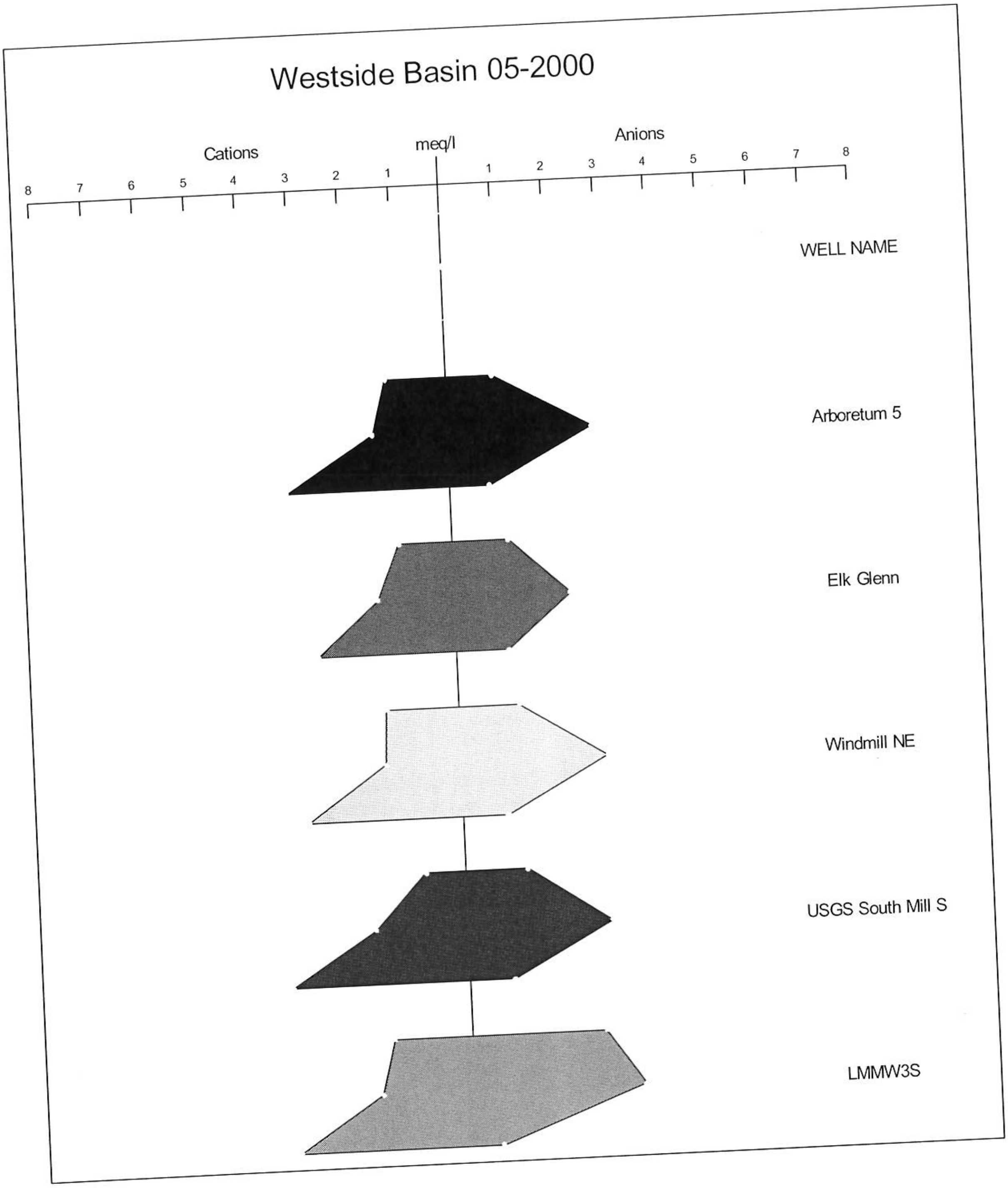


Figure 3.22a: *Stiff diagrams for wells sampled in May 2000.*

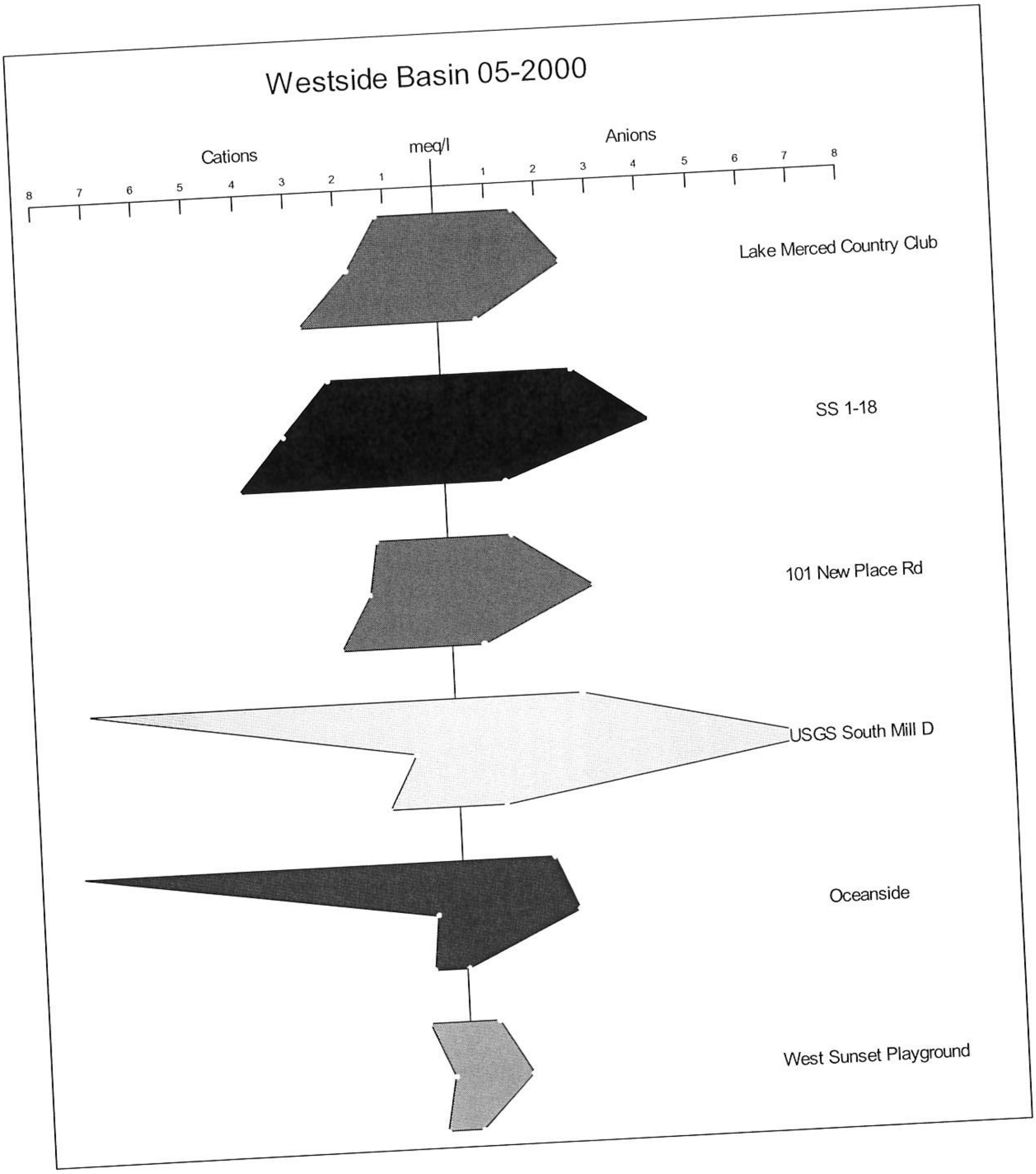


Figure 3.22b: *Stiff diagrams for wells sampled in May 2000.*

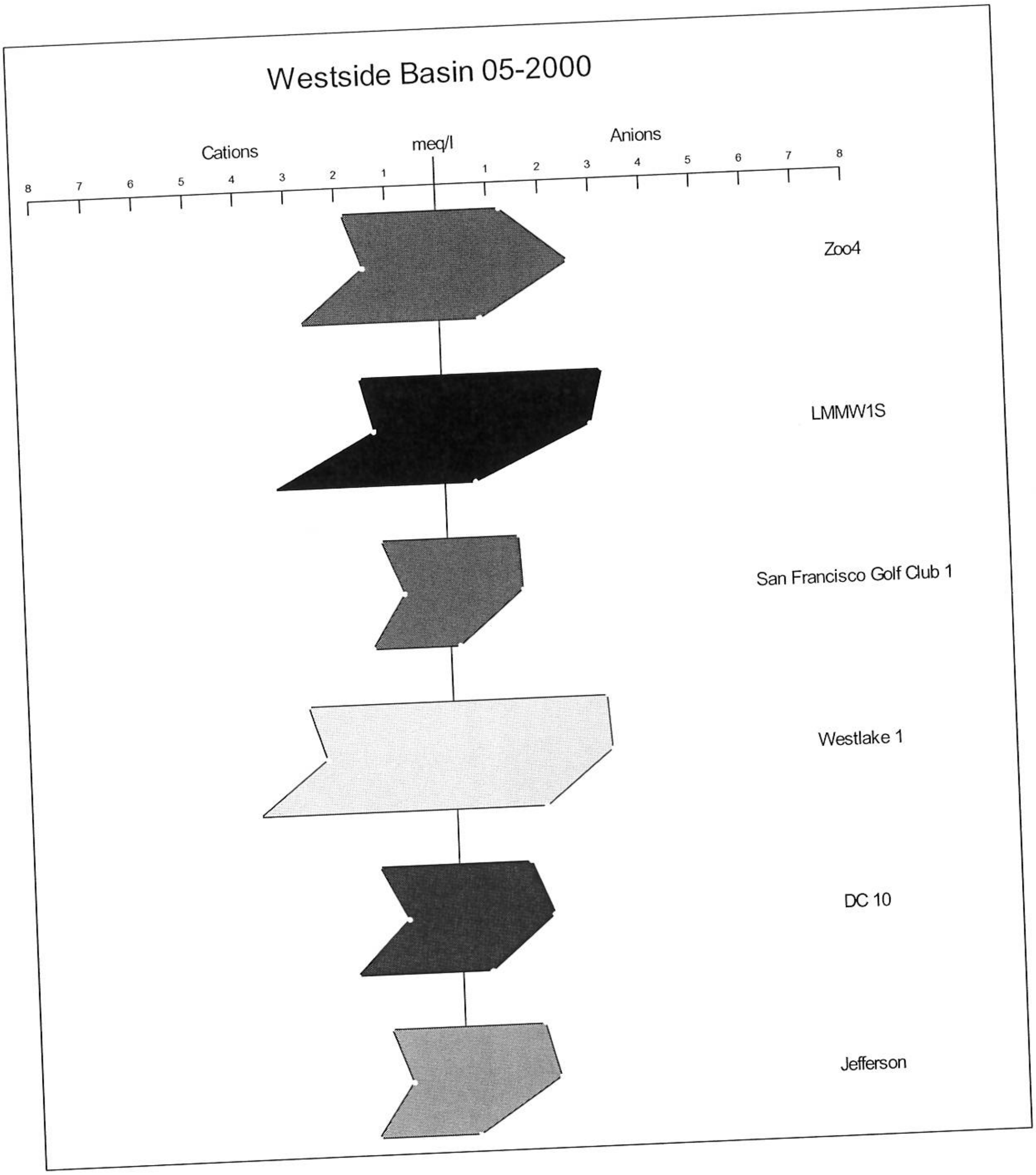


Figure 3.22c: *Stiff diagrams for wells sampled in May 2000.*

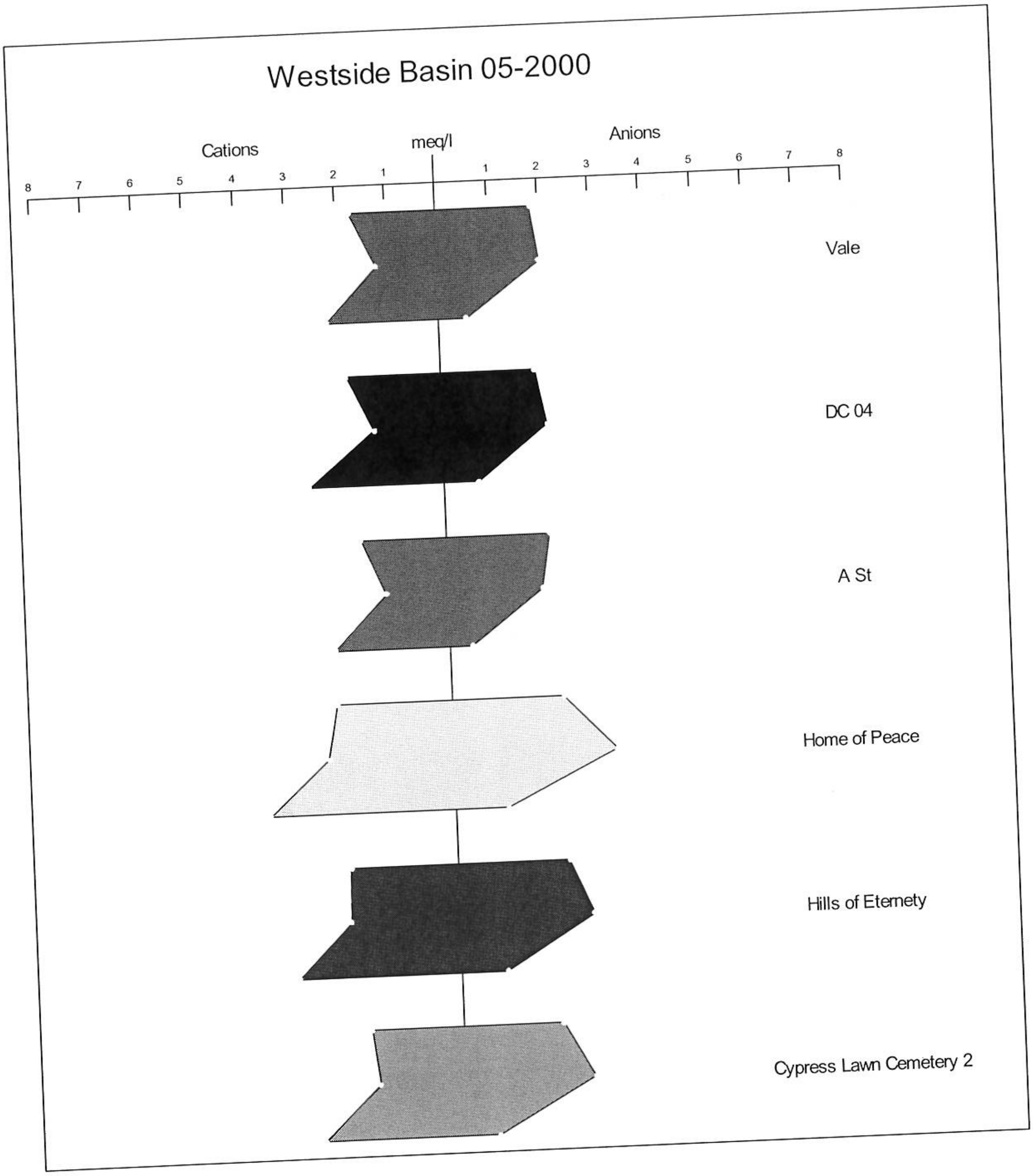


Figure 3.22d: *Stiff diagrams for wells sampled in May 2000.*

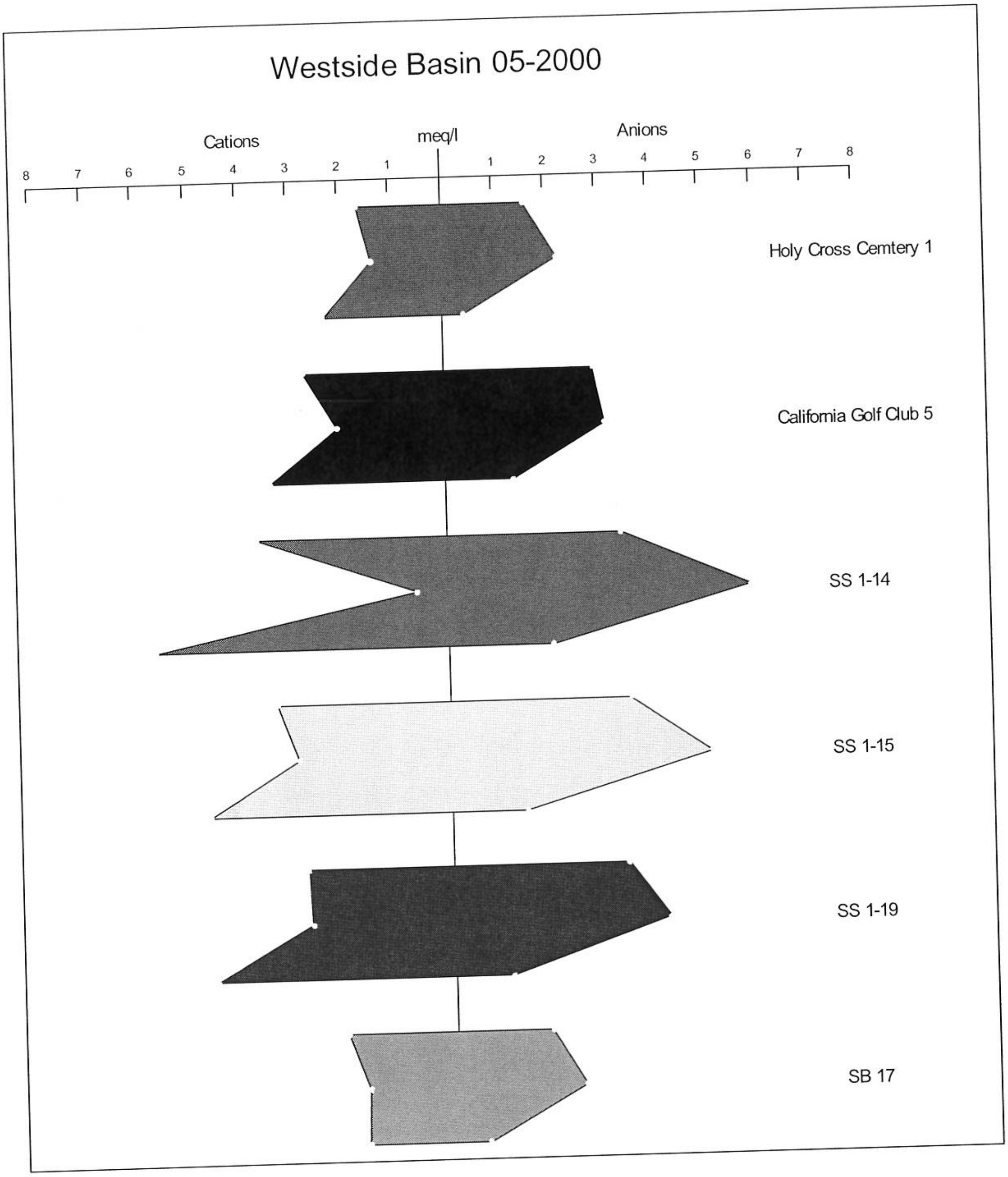


Figure 3.22e: *Stiff diagrams for wells sampled in May 2000.*

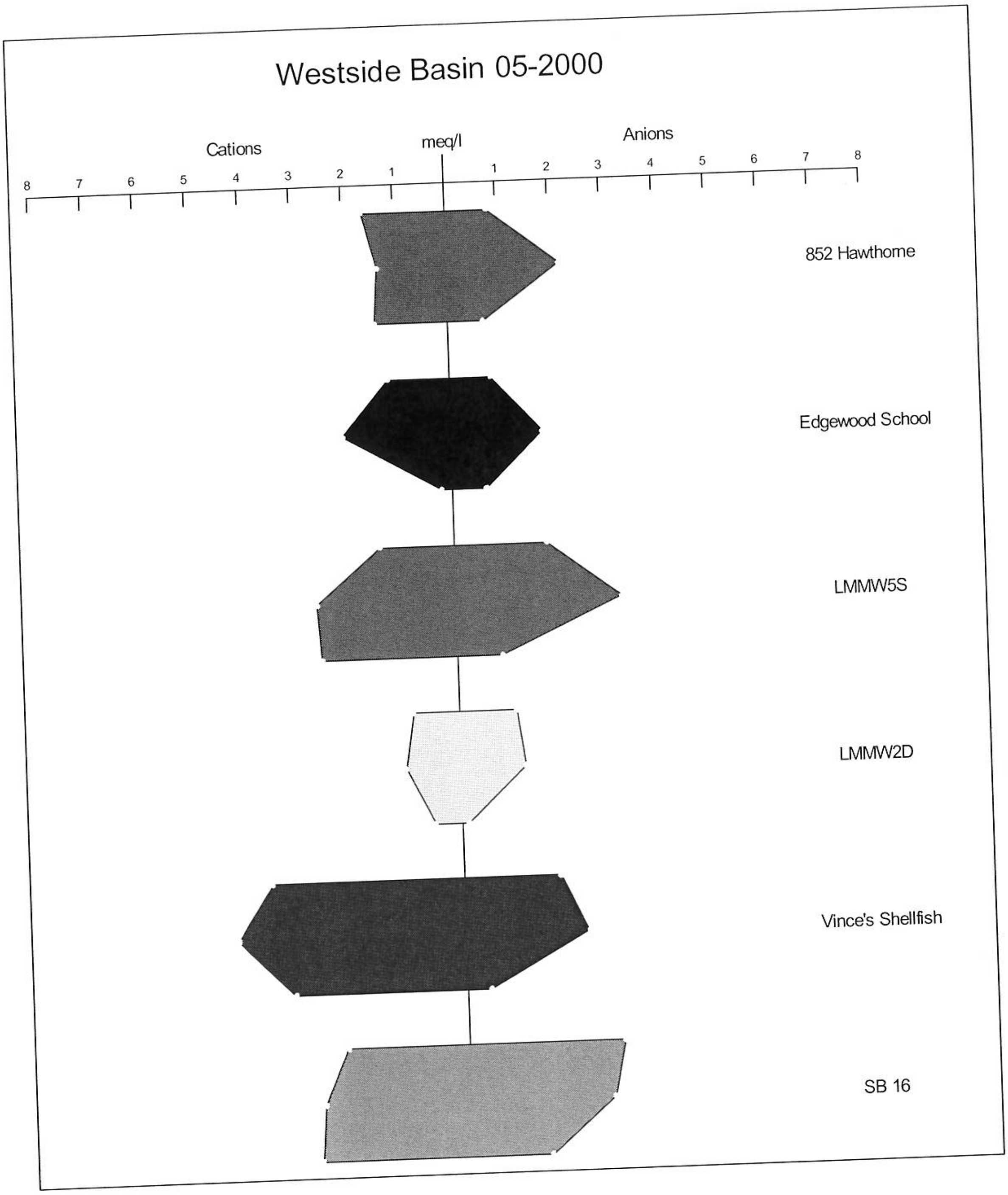


Figure 3.22f: *Stiff diagrams for wells sampled in May 2000.*

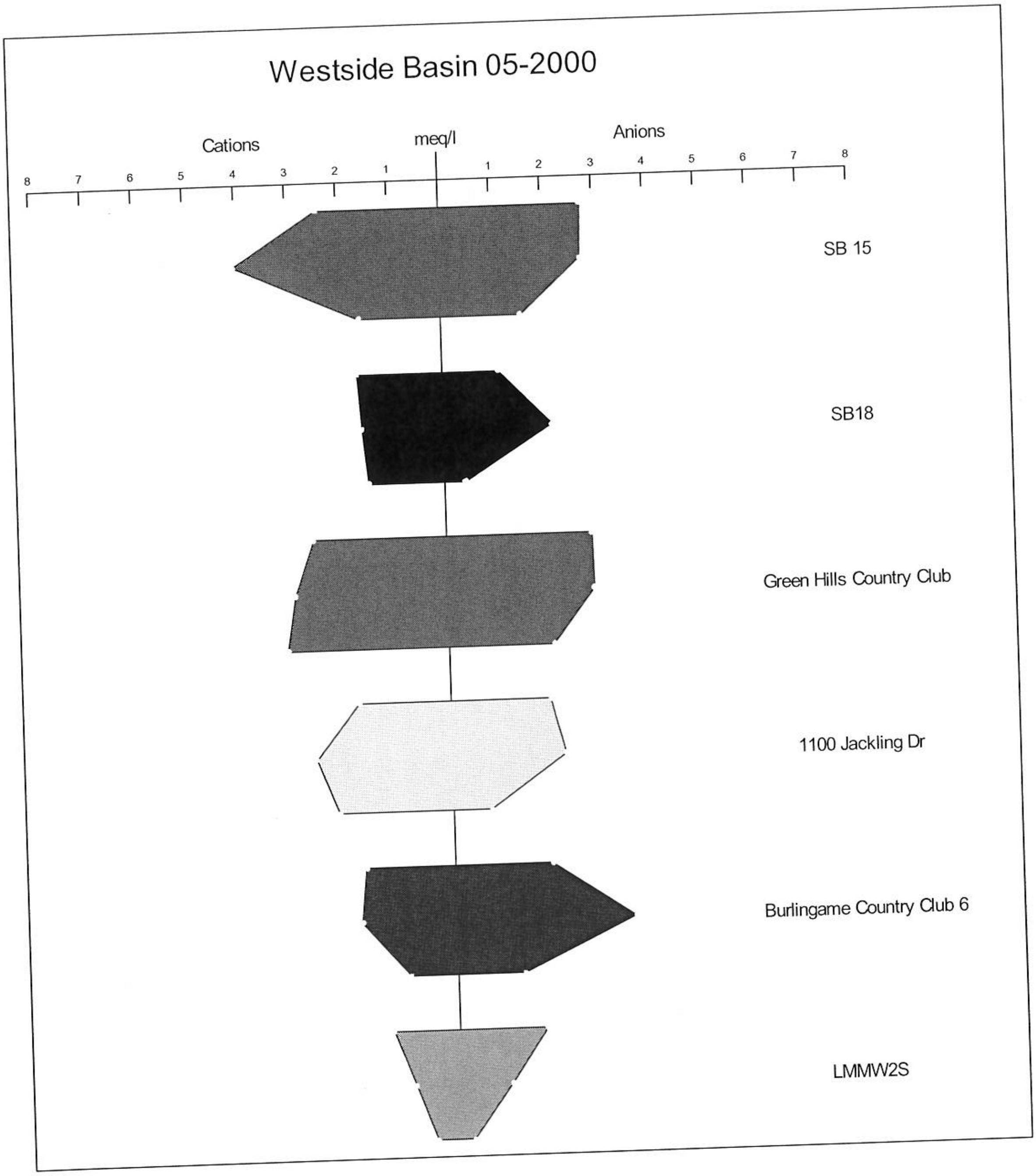


Figure 3.22g: *Stiff diagrams for wells sampled in May 2000.*

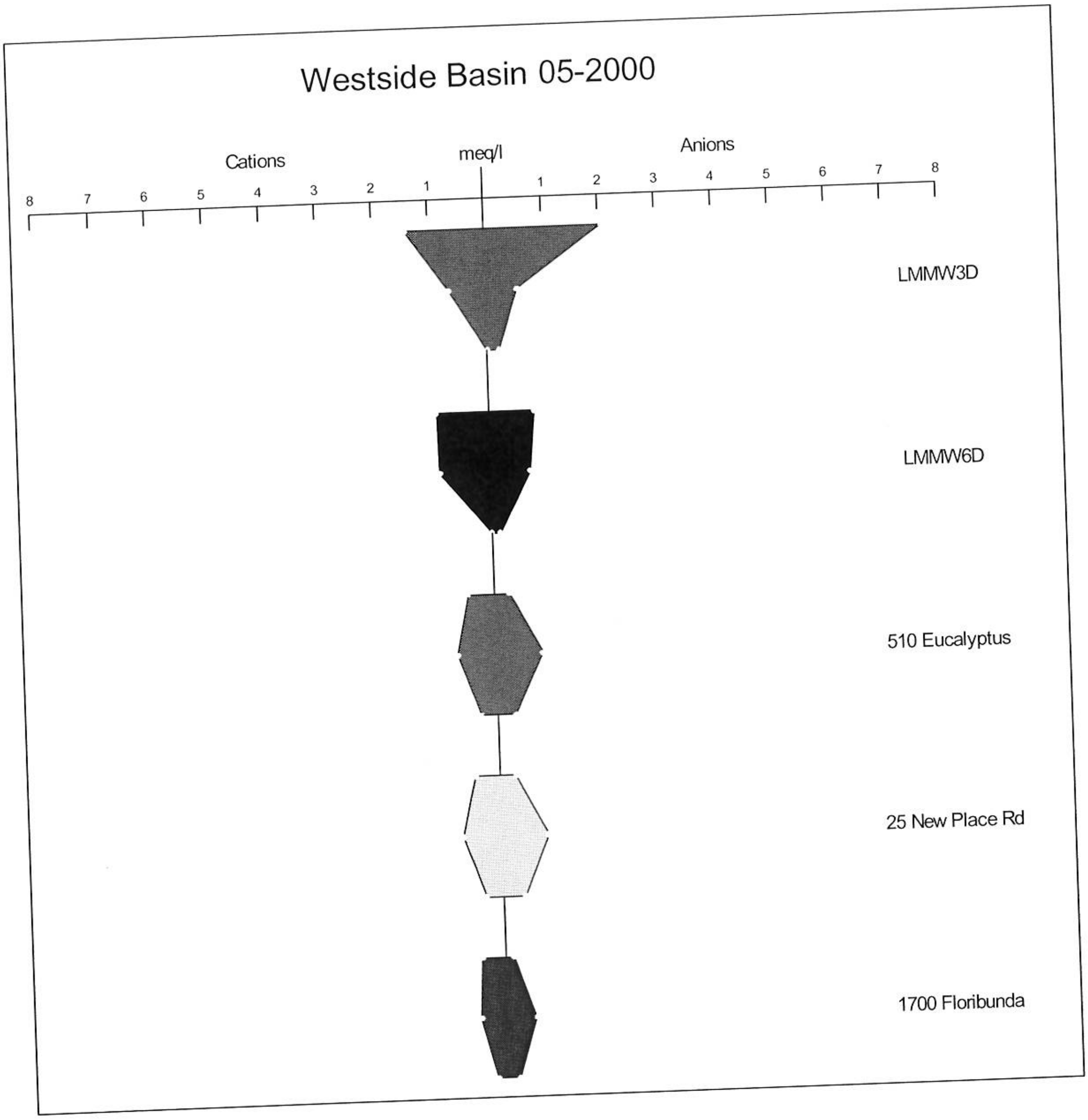


Figure 3.22h: *Stiff diagrams for wells sampled in May 2000.*

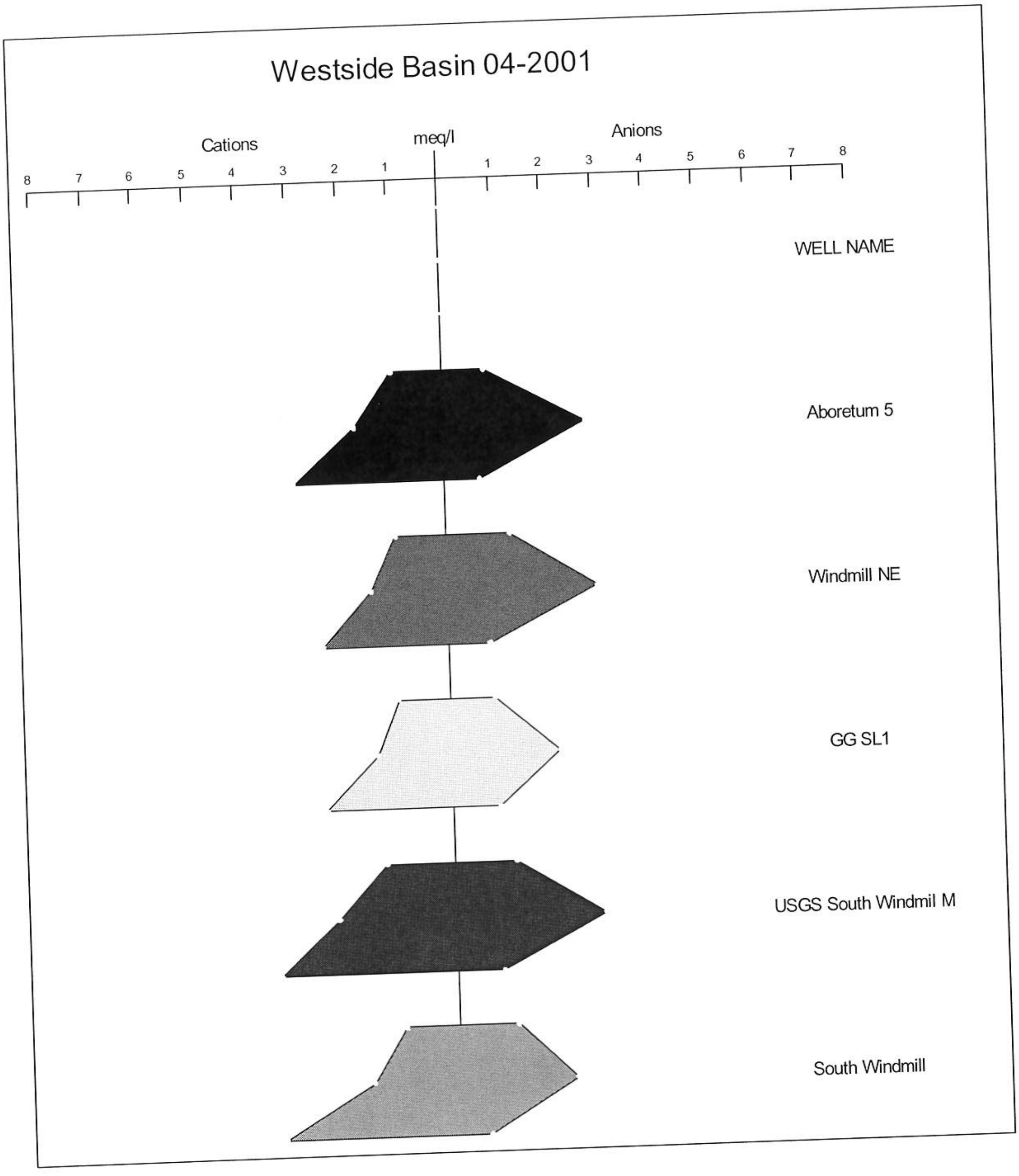


Figure 3.22i: *Stiff diagrams for wells sampled in April 2001.*

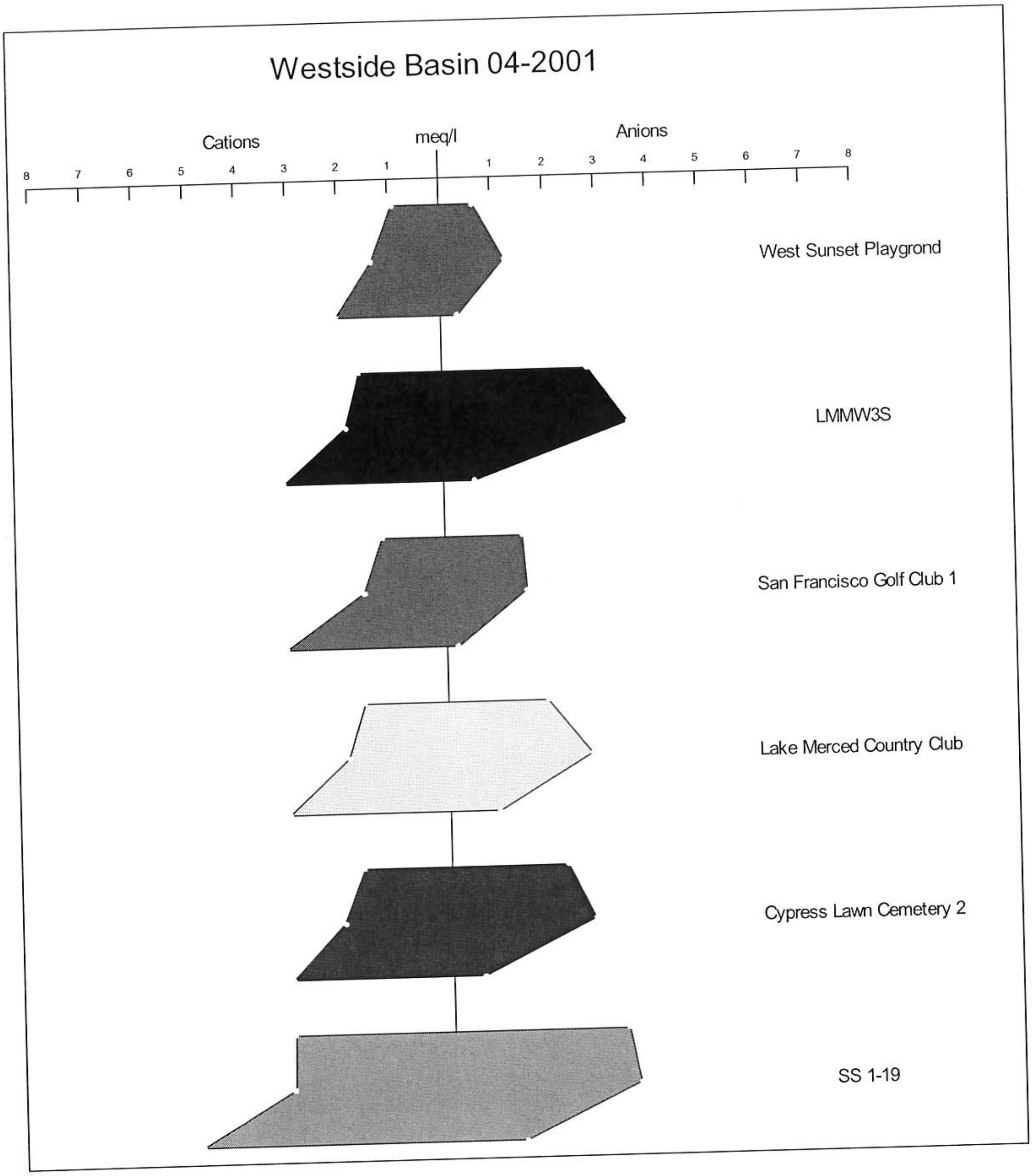


Figure 3.22j: *Stiff diagrams for wells sampled in April 2001.*

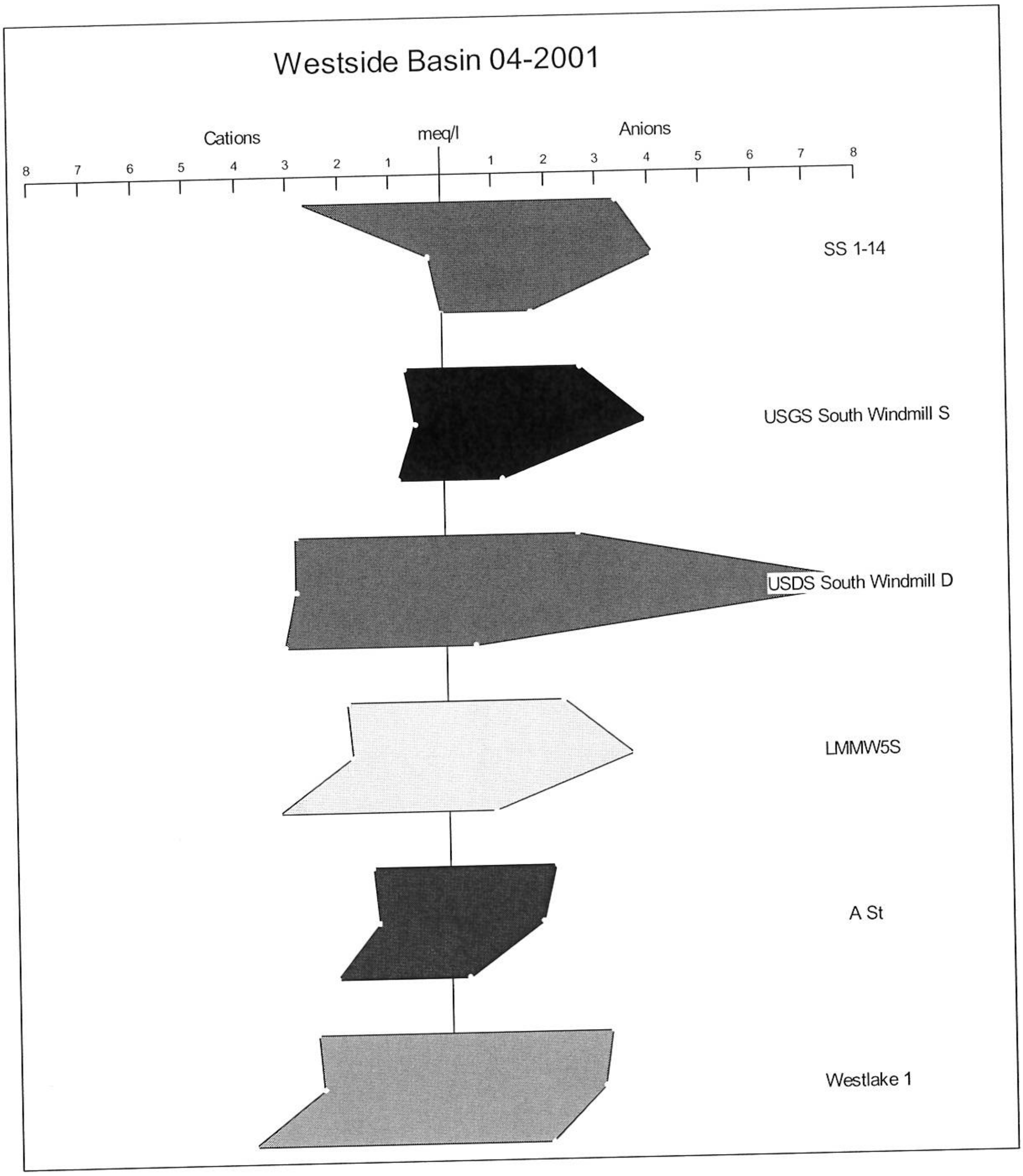


Figure 3.22k: *Stiff diagrams for wells sampled in April 2001.*

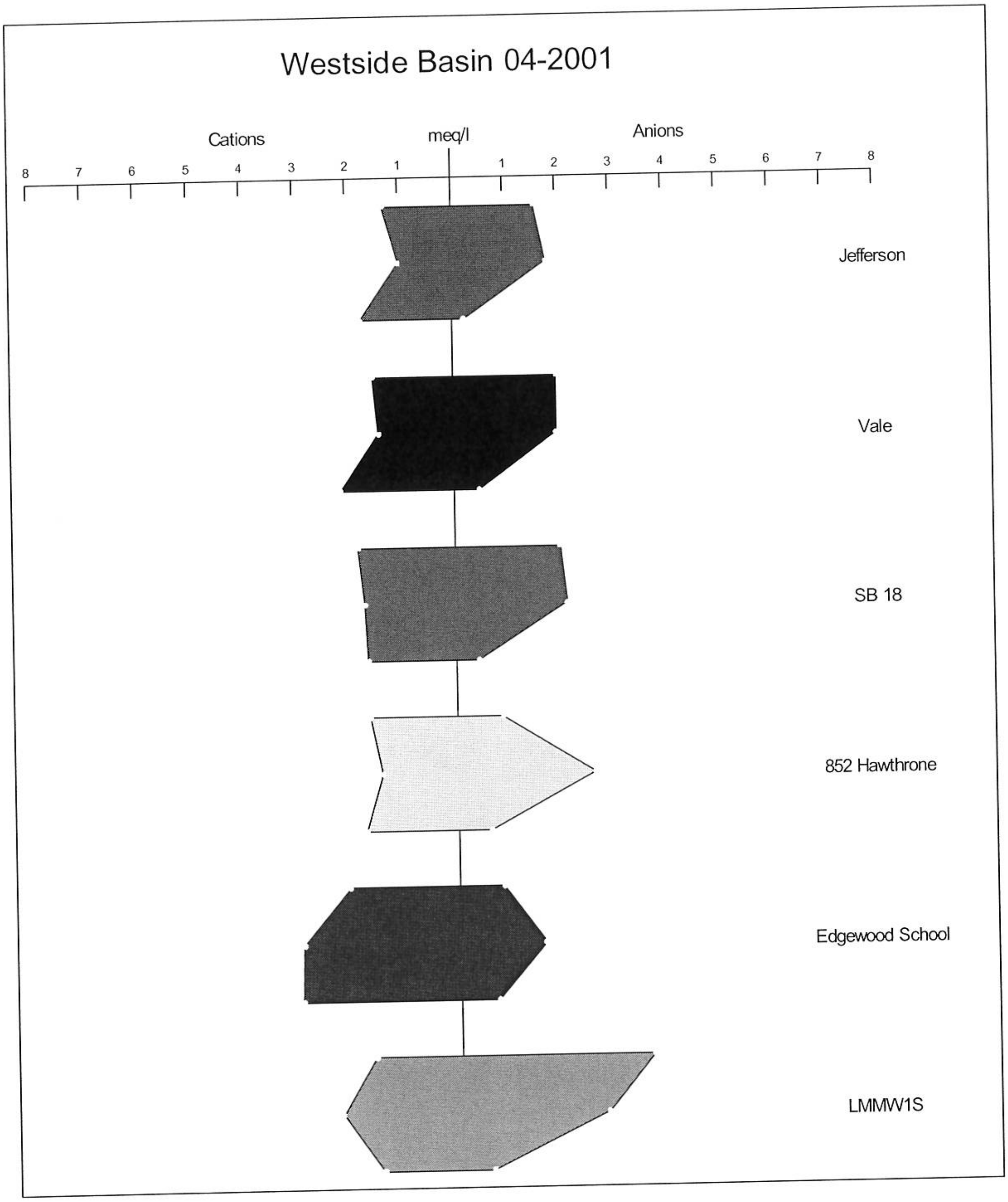


Figure 3.211: *Stiff diagrams for wells sampled in April 2001.*

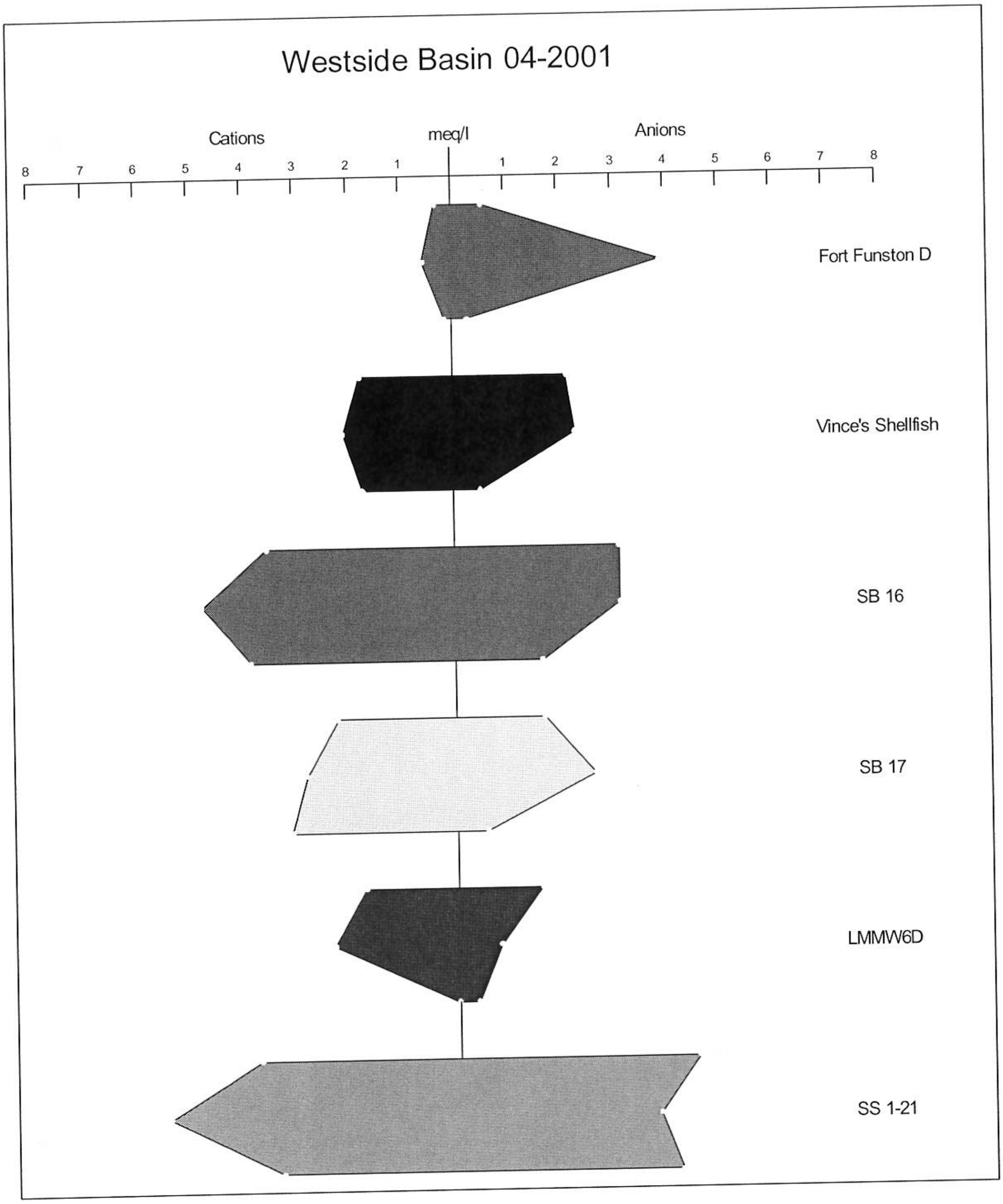


Figure 3.22m: *Stiff diagrams for wells sampled in April 2001.*

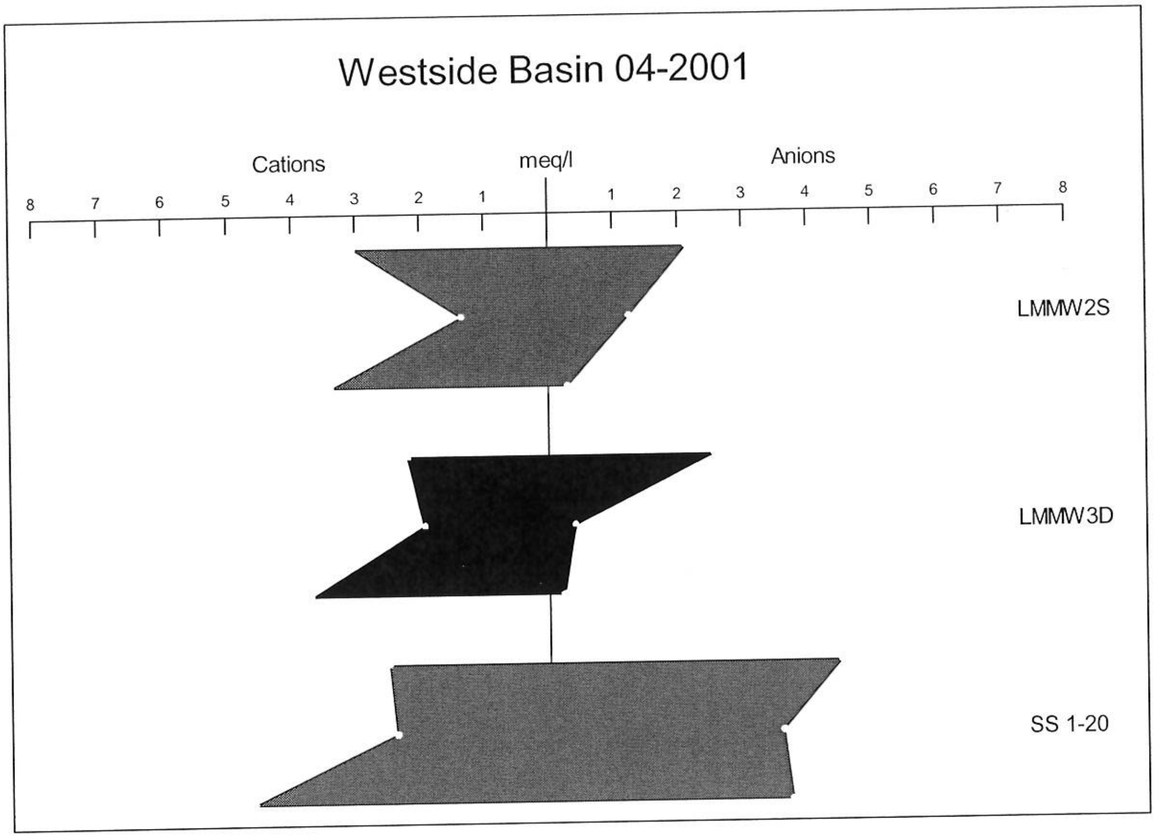


Figure 3.22n: *Stiff diagrams for wells sampled in April 2001.*

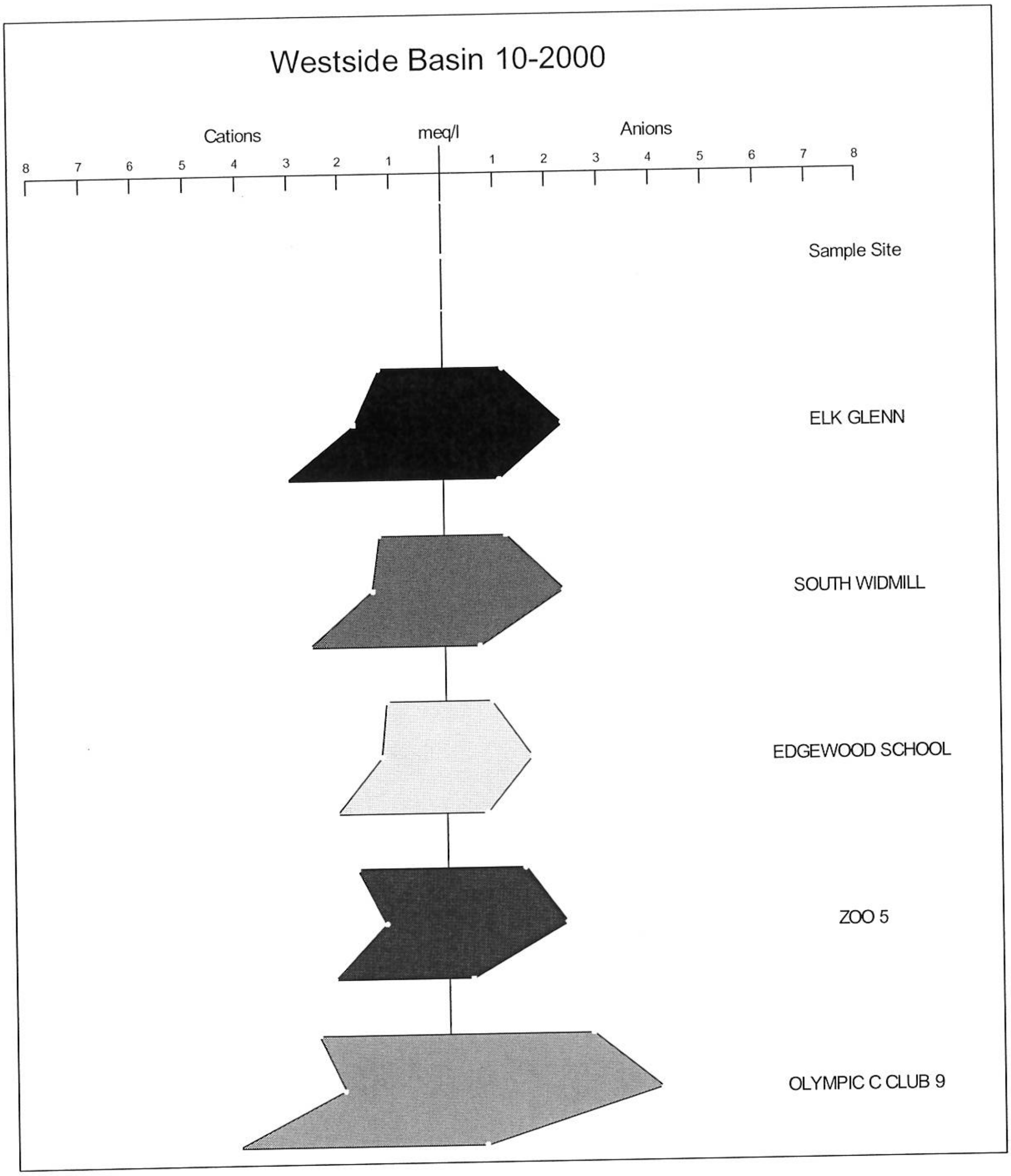


Figure 3.22o: *Stiff diagrams for wells sampled in October 2001.*

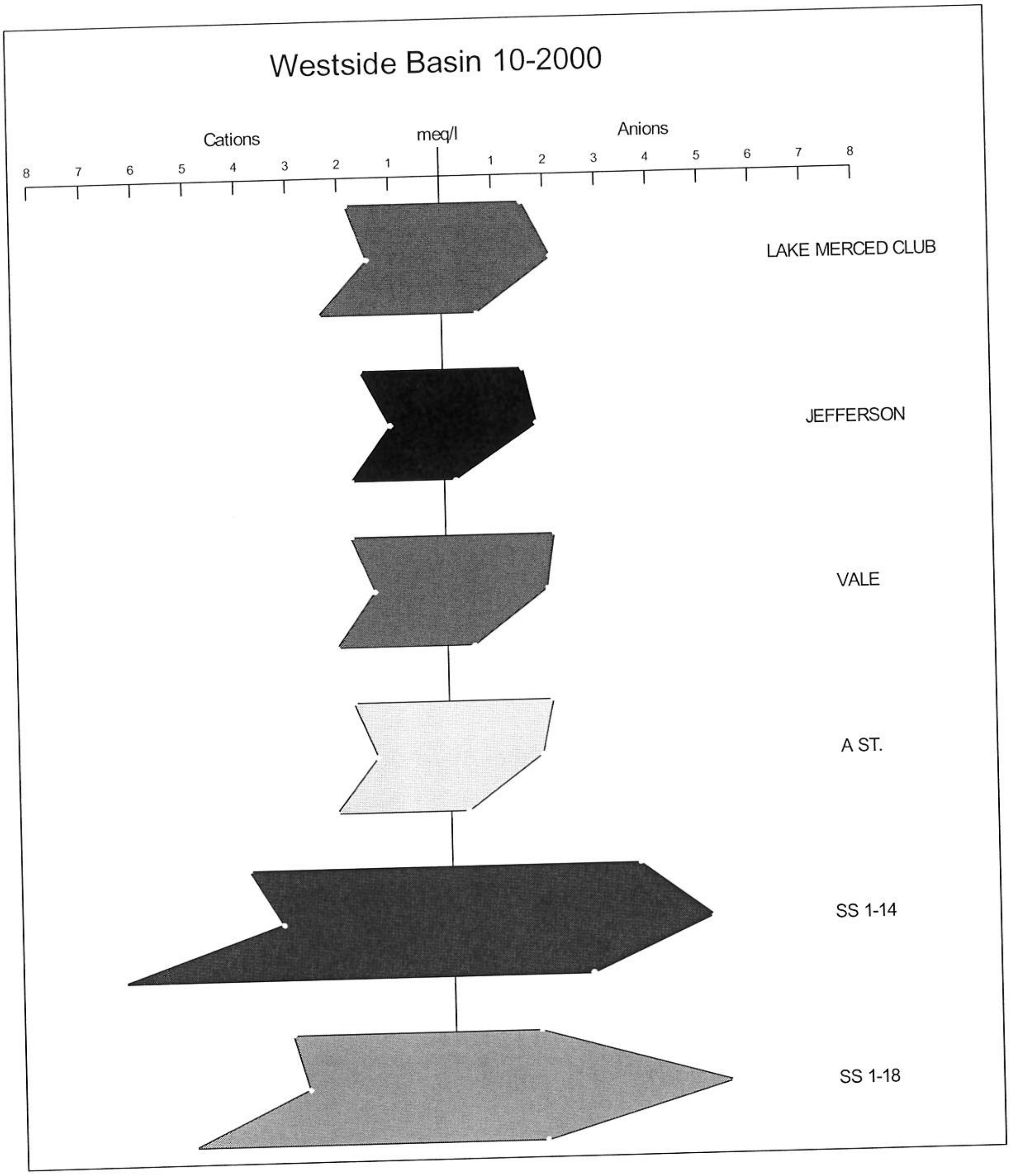


Figure 3.22p: *Stiff diagrams for wells sampled in October 2001.*

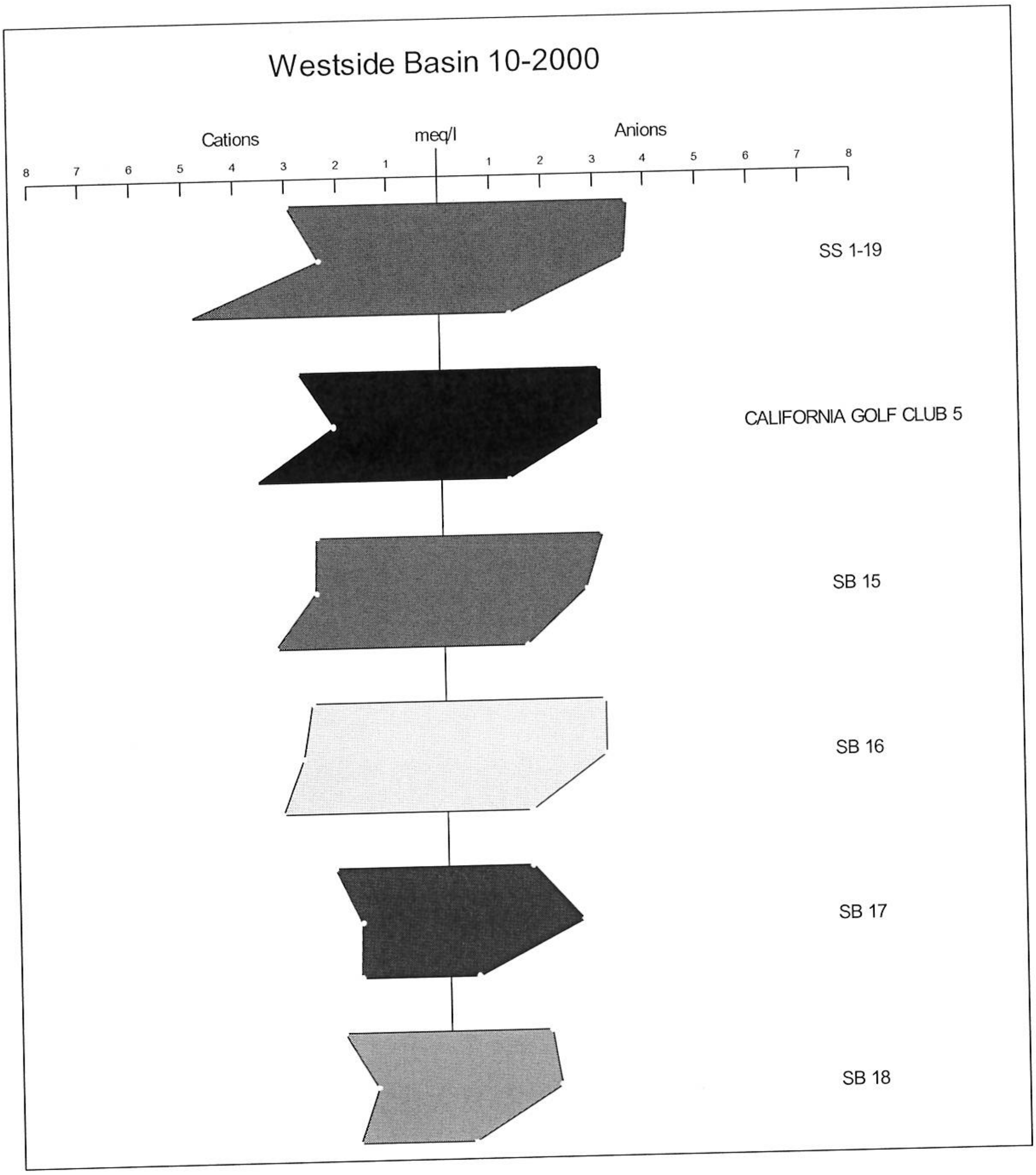


Figure 3.22q: *Stiff diagrams for wells sampled in October 2001.*

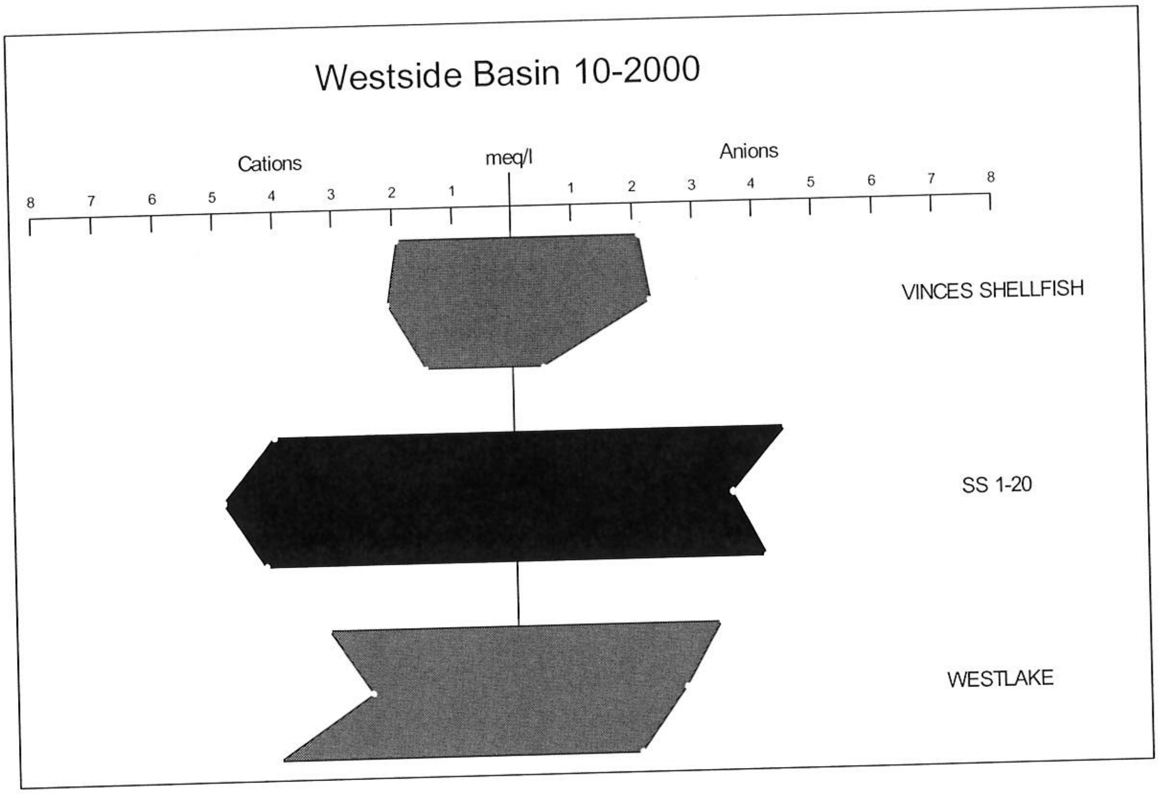


Figure 3.22r: *Stiff diagrams for wells sampled in October 2001.*

3.3.3 Stable isotopes:

Stable isotopes can be used in groundwater studies to determine two different characteristics, first the source of water and second its age. The source of water can be determined based on hydrogen-2 (^{2}H, deuterium) and oxygen-18 (^{18}O). Since the concentration of these isotopes in precipitation decreases inland it is easy to determined whether coastal groundwater is recharged by local precipitation or imported inland water. This is especially vital for coastal cities that import water from far away sources and allows an assessment of how much imported water leaks from water mains and recharges the local groundwater. Natural concentration of both isotopes ranges from 0.01% to 0.2%, where the higher concentrations are generally found closer to the ocean and the lower further inland in continents. Ocean water is concentrated in heavy isotopes (Hem 1985). During evaporative processes the lighter isotopes tend to evaporate faster and in greater amounts than the heavy isotopes. Once water vapors move inland condensation and evaporation cycles tend to decrease the heavy isotope concentration of water vapors the further inland these move (Yates et al. 1990). In the case of California, therefore, water in the coastal areas has a higher concentration of deuterium and oxygen-18 than water in the Sierra Nevada. In the San Francisco Bay Area, where water from the Sierra Nevada (Hetch Hetchy water) is imported to supply local demand, leaking water mains end up recharging local groundwater. For the Westside Basin, analyzing for these isotopes can aid in identifying different water bearing zones. In the upper water bearing zones, which are probably more recently recharged, there will be a higher percentage of imported water and, therefore, lower deuterium and oxygen-18 concentrations. In contrast, the lower water bearing zones will contain less imported water (possibly none at all) and , therefore, higher deuterium and oxygen-18 concentrations.

Deuterium and oxygen-18, in general, correlate linearly. Therefore, a graphic representation, known as meteoric water line, can be used for comparison with water sampling results. Yates et al. (1990) analyzed samples from various wells in the Golden Gate Park and around Lake Merced for deuterium and oxygen-18 and compared the values with those of municipal water. They concluded that municipal water enriched in isotopes through evaporation recharged groundwater at the Arboretum wells. In general, the shallow water-bearing zones seem to have isotopic ratios that are much closer to municipal water composition than in the deeper water bearing zones (Phillips et al. 1993).

Furthermore, Yates et al. (1990) noted that Lake Merced samples plotted to the right of the meteoric water line due to higher concentration of isotopes by evaporation. Similar concentration values were found in the HLA as well as in the Olympic Country Club wells, both of which are located close to Lake Merced. These same wells also show slightly higher chloride concentrations, which, too, can be caused by evaporative effects (Yates et al. 1993). These observations lead Yates et al. (1990) to conclude that Lake Merced locally recharges the groundwater basin and, therefore, influences the geochemical composition of wells downgradient from it.

Groundwater age dating techniques can be of extreme help in identifying different water bearing zones, especially in multilayered groundwater basins like the Westside Basin. Since vertical migration between one water bearing zone and another is retarded by the presence of clay layers the age of the groundwater should be greater in deeper water bearing zones than in shallower zones. Therefore, knowing the age of groundwater in a water bearing zones allows correlating this zone across different wells in the basin.

Tritium is the most common isotope used for age determination of water. Tritium is a radioactive isotope of hydrogen that was enriched in the atmosphere since the 1950's as a result of nuclear testing. The peak in tritium concentration in the atmosphere occurred in 1963 (Phillips et al., 1993). Water exposed to the atmosphere at that time and subsequently entered the groundwater basin will contain a unique tritium signature. Phillips et al. (1993) analyzed well in the western part of San Francisco as well as at the San Francisco International Airport and noticed that groundwater in the shallow water bearing zones (up to 15 meters) contained high concentrations in tritium, but lower than those of the 1963 tritium peak. They concluded that water in shallow aquifers are recently recharged. The deeper water bearing zones, however, showed very low tritium concentrations, which indicate that the water is more than 50 years old. Guidetti and Schaefer (1995) noted that the deep USGS monitoring well at the San Francisco International Airport is screened in the same water bearing zones as most of the deep municipal wells in San Bruno. Based on this observation they concluded that the water of the San Bruno municipal wells has the same old age as water encountered in the deep USGS well. The deep water bearing zones from where San Bruno extracts water must, therefore, be separated from the shallower zones by one or more confining zones.

Lawrence Livermore National Lab (Moran, J. written communication 2001) carried this idea of age dating of water further out and analyzed wells in Daly City, San Bruno and Millbrae not only for tritium but also helium (^4He), oxygen-18 and noble gas isotopes, as well as volatile organic compounds (VOC) on a ?g/L basis, in order to further refine the age constraints. The refinement in the age dating procedure is for both very old (more than 50 years) and very recently (2 to 5 years) recharged water. While very old water will be enriched in noble gas and ^4He isotopes, very young water will contain higher concentrations of VOC on a ?g/L basis. Samples were collected at Jefferson well and Vale well in Daly City, SB15 in San Bruno, and 852 Hawthorne in Millbrae. The 852 Hawthorne well has a shallower top of screen interval than all the other three wells (Table 4.1). For this well the analytical results indicate higher tritium concentration and very low ^4He concentrations. However, tritium is negligible in concentration in all other three wells; nevertheless, a substantial amount of ^{4}He is present. The contrasting concentrations in tritium and ^{4}He point to different sources of water from which well 852 Hawthorne draws water compared to Jefferson, Vale and SB15 wells. Furthermore, the concentrations indicate that the water pumped at well 852 Hawthorne was recently recharged, while the water at Jefferson, Vale and SB15 wells is very old. The estimated age of the water at Jefferson and Vale wells is 100 years, while at SB15 is 700 years.

Chapter 4

BOUNDARY DELINEATION OF THE WESTSIDE BASIN

4.1 Introduction:

After a thorough review of all available geologic and hydrogeologic data described in chapter 2 and 3 cross sections and water level contour maps have been generated. Both cross sections (Plates A, B, C and D) and water level contour maps (Figure 4.5) were used to determine the horizontal boundaries of the Westside Basin, in particular, the southern boundary, which so far had not been properly defined. To determine the vertical boundaries, i.e. the bottom of the groundwater basin as well as the different hydrostratigraphic units water quality parameters and well construction details were used in conjunction with geologic cross sections. In this chapter the data collection efforts, field work as well as the development of the maps and cross sections is described and the results of these analysis are presented.

4.2 Methods and Materials:

The vast majority of currently existing wells in the Westside Basin were located with a Trimble ProXR GPS unit that has a submeter instrumental accuracy (Trimble 1999). All other wells, to which access was not possible or that have been destroyed were located based on site location description mentioned in well logs, reports or other records made available by San Mateo County Environmental Health, California Water Service Company, Daly City Water and Wastewater Department and San Bruno Public Works. GPS and hand placed well locations were compiled using ArcView 3.2. The map showing the location of all the wells (Figure 3.1) as well as all other maps generated using this program are in the Albers Projection.

The majority of the geologic information comes from well logs. The quality of these well logs varies. In general, well logs for monitoring wells associated with site contamination remediation activities and wells logged by the US Geological Survey are more detailed in their geologic description and were used when possible. The description found in most of these monitoring wells follows the unified soil classification system (USCS) (Appendix B). However, the geological description of irrigation and drinking water wells does not follow the USCS and, therefore, the description can be very subjective. In addition, the terminology used by one well driller differs substantially from another. Consequently, one would be inclined to prefer using well logs where the USCS was used to describe the lithology. However, the vast majority of these logs are for wells that penetrate the ground to a depth of approximately 6 meters. In order to obtain information on the lithology at greater depths other well logs, despite their lower descriptive quality, have to be taken into consideration. Therefore, cross-sections developed based on such well logs (Appendix C) should be viewed with discretion. They have to be regarded as showing general trends on a small map scale and not as definite for a specific location on a large map scale.

Geologic maps were taken into consideration for the development of the cross sections. In particular, maps by Bonilla (1965, 1971, 1998), Pampeyan (1994) and Schlocker (1974) were routinely used in cross section delineation. The maps provided information on the surface geology, location of faults, synclines and anticlines and strike and dip values of beds. This information was especially important for the area between the San Andreas and Serra faults where the sediments of the Merced Formation are folded. Further surface and subsurface geologic information was obtained from individual reports. These include Bonilla (1959), Atwater et al. (1977) and Bonilla et al. (2000). Bonilla (1959) developed a geologic map for the Westlake District in Daly City. His report contains pertinent information on the attitude of the beds of the Merced Formation in that area. Additionally, the report mentions the location of outcrops of the Rockland Ash. The location of these outcrops allows the identification of Clifton and Hunter's (1989) sequence S, in which the Rockland Ash is embedded. Atwater et al. (1977) contains a map showing the historic extent of the Bay Muds along the San Francisco Bay. Their report also includes a general description of the sediments encountered at depth in the San Francisco Bay and at one location mentions an ash found in one boring in the San Francisco Bay. Bonilla et al. (2000) contains some cross sections and a description of the geologic materials found in the area from Daly City to San Bruno. Information derived from these reports was incorporated in the cross-sections developed in this report.

Clifton and Hunter's (1989, 1991 and 1999) description of the sequences of the Merced Formation and their location along the coastal bluffs between Mussel Rock and Fleischhacker Zoo was included in the cross sections. The description of the different sediments of the Merced Formation was compared with that of the Unified Soil Classification System (USCS) (Appendix B) to help identify the individual sequences of the Merced Formation inland from the coastal bluffs. Furthermore, an attempt was made to delineate in the cross sections the sequences of the Merced Formation and name them after Clifton and Hunter's (1989) nomenclature.

Bedrock elevation was derived from maps by Bonilla (1964), Hensolt and Brabb (1990) and Phillips et al. (1993). Each of these maps was generated by the authors using available boring logs and geophysical information at the time they were compiled. All three maps cover different areas within the Westside Basin. Therefore, in order to obtain one common bedrock elevation map the bedrock elevation contours on all three maps were digitized and mosaiced using ArcInfo 7.0. This compiled bedrock elevation map (Figure 4.1) was used to determine the bottom of the groundwater basin in the cross sections. Locally, the bottom of wells that show unconsolidated sediments in their well log descriptions is deeper than the bedrock elevation for the same spot. In these cases the bedrock elevation was corrected downwards. Due to local uncertainties the bedrock elevation in all cross sections is dashed.

The location of the faults in all cross sections is based on Brabb and Olson (1986). Their map was digitized using ArcInfo 7.0 and overlain on the Bonilla's (1998) and Brabb et al. (1998) digital geologic maps. Locally, the location of the Serra fault was corrected based on recent information by Barr (1999) and Kennedy (2002). This compiled fault map (Figure 4.2) was used to properly locate the fault traces on the cross-sections. However, since the exact vertical extent and trace of the faults in mostly unknown the faults are shown dashed in the cross-sections.

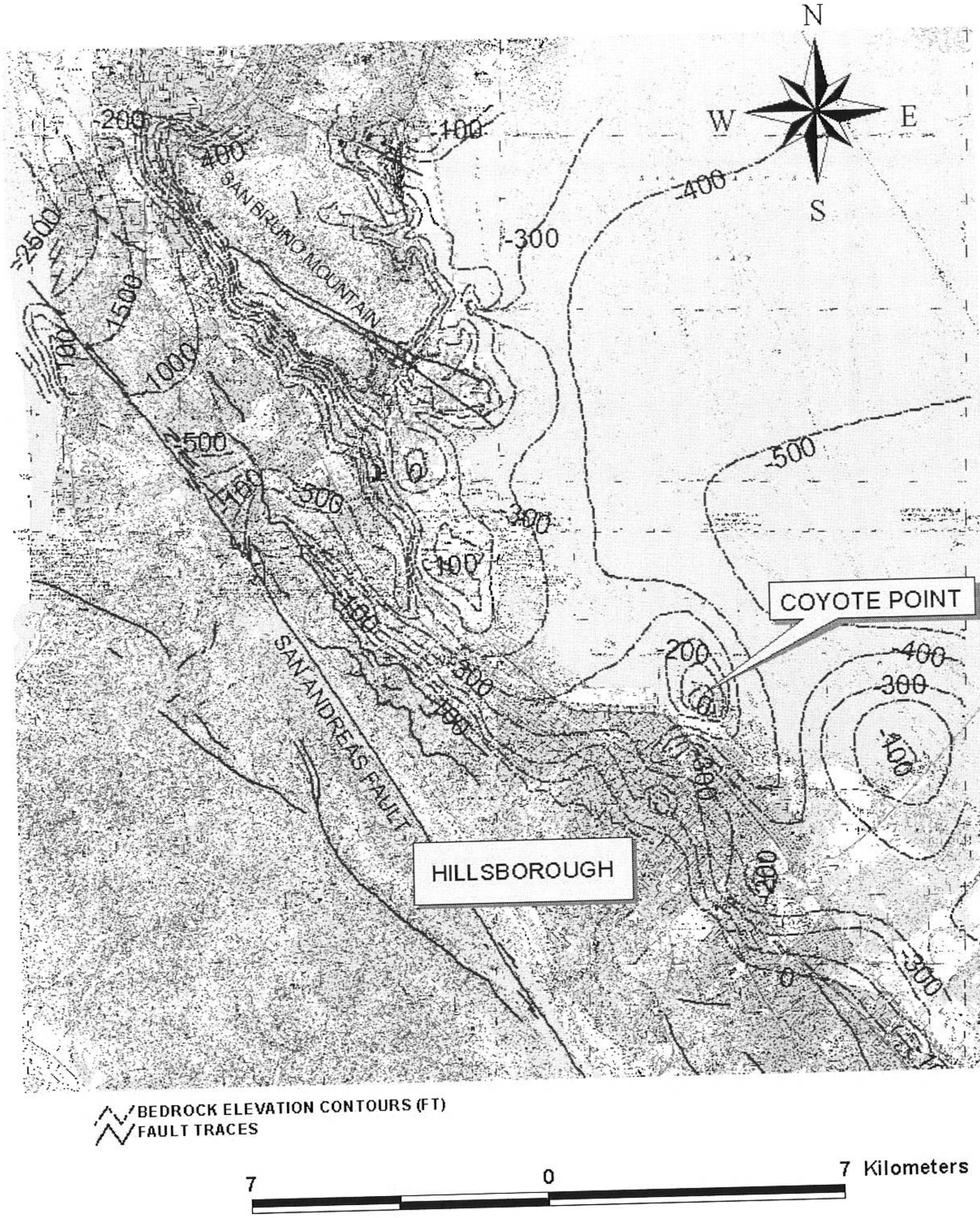


Figure 4.1: *Bedrock elevation contours in the Westside Groundwater Basin. Data compiled from Bonilla (1964), Hensolt and Brabb (1990) and Phillips et al. (1993). Bedrock elevation is in feet.*

Figure 4.2: *Location of faults and strike and dip values. Compiled from Bonilla (1959, 1965, 1971), Brabb and Olson (1986), Clifton and Hunter (1989, 1991, 1999) and Pampeyan (1994).*

Water level data was used alongside geologic and bedrock elevation information in order to determined the southern boundary of the Westside Basin. That type of data was compiled by year for various wells in the basin from available well logs and other records provided by and San Mateo County Environmental Health Division. The maps and associated piezometric surface (Figure 4.4) were generated for the area from Millbrae in the north to San Mateo and Foster City in the south using ArcView version 3.2, with the ArcView Spatial Analyst version 2.0 extensions (see section 3.2).

All cross sections (Plates A, B, C and D) were hand drawn. A total of four cross sections were drawn trending southwest-northeast (Figure 4.3). The southwest-northeast trending cross sections were drawn first. After the cross sections were drawn they were all scanned in parts. The parts were then merged in Adobe Photoshop 5.0 and edited in Adobe Illustrator 10.0. Information on well construction details and subdivision of the hydrostratigraphic units were added to the cross sections during the final editing process.

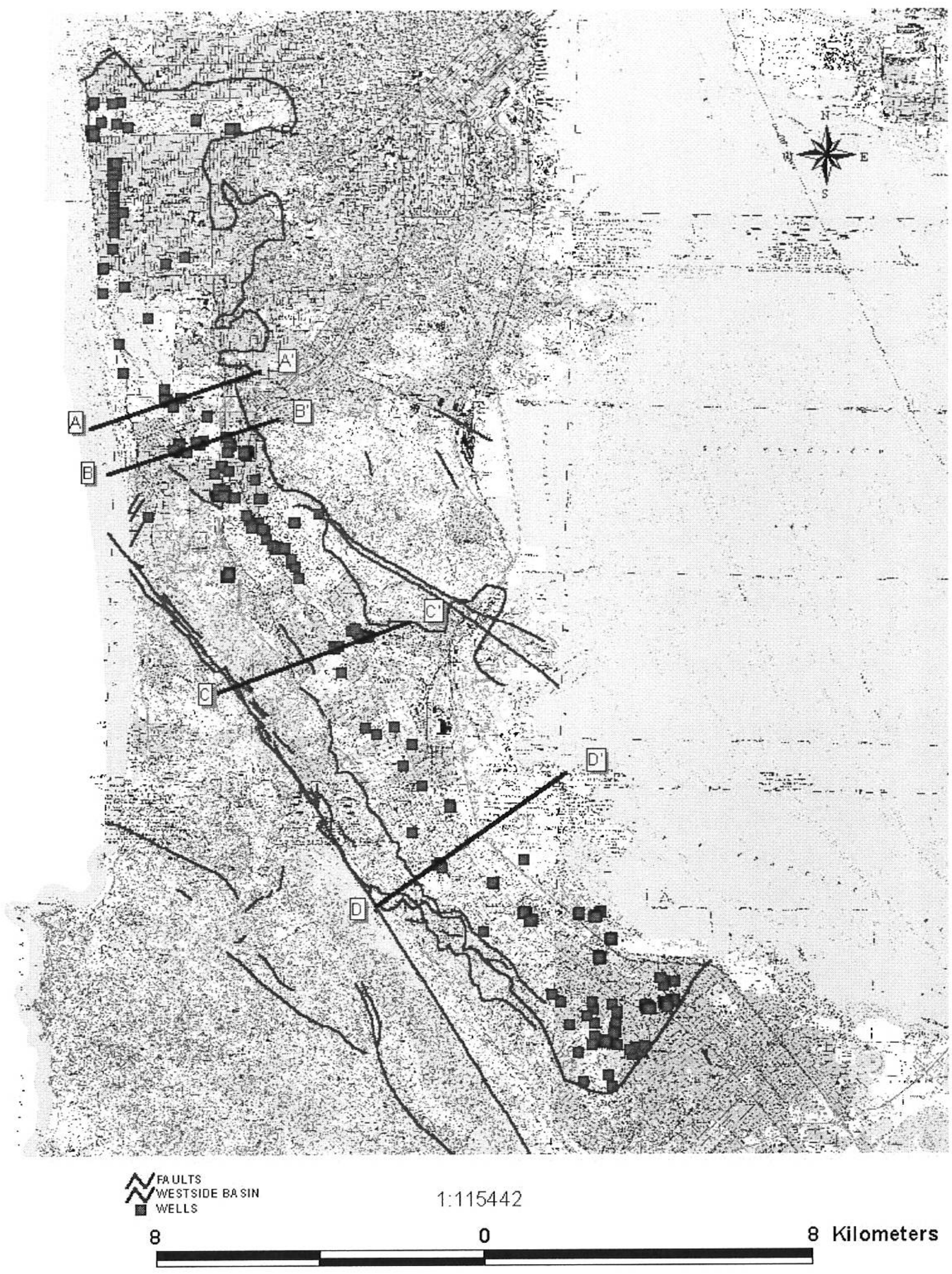


Figure 4.3: *Map showing the location of cross sections A-A', B-B' C-C' and D-D'.*

4.3 Results

4.3.1 Southern Boundary

The compiled bedrock elevation map for the northern part of the San Francisco Peninsula (Figure 4.2) shows a deep northwest-southeast valley, in which all the unconsolidated sediments of the Merced and Colma formations are deposited. This valley is deepest in the northwest where it reaches depths of over 1,000 meters below sea level. The bottom of the valley shallows upward towards the southeast. In the area between Hillsborough and Coyote Point the valley floor lies at 6 meter below sea level. South of this area the bedrock surface decreases in elevation again, to depths of about 100 meters below sea level. The area between Hillsborough and Coyote Point can, therefore, be considered a "bedrock high".

Water level data for various wells deeper than 30 meters in the area from Millbrae in the north to San Mateo and Foster City in the south was grouped by year. Water level contour maps were generated for the years 1950, 1953, 1977, 1988, 1989, 1990, 1991 and 1993 (Figure 4.5). All of these contour maps indicate a potentiometric high trending southwest-northeast. Northwest of this potentiometric high groundwater flows to the north and northwest. Southeast of the potentiometric high groundwater flows to the east and southeast. This potentiometric high lines up with the "bedrock high" between Hillsborough and Coyote Point (Figure 4.6). It seems, therefore, plausible to consider this area the southern boundary of the Westside Groundwater Basin.

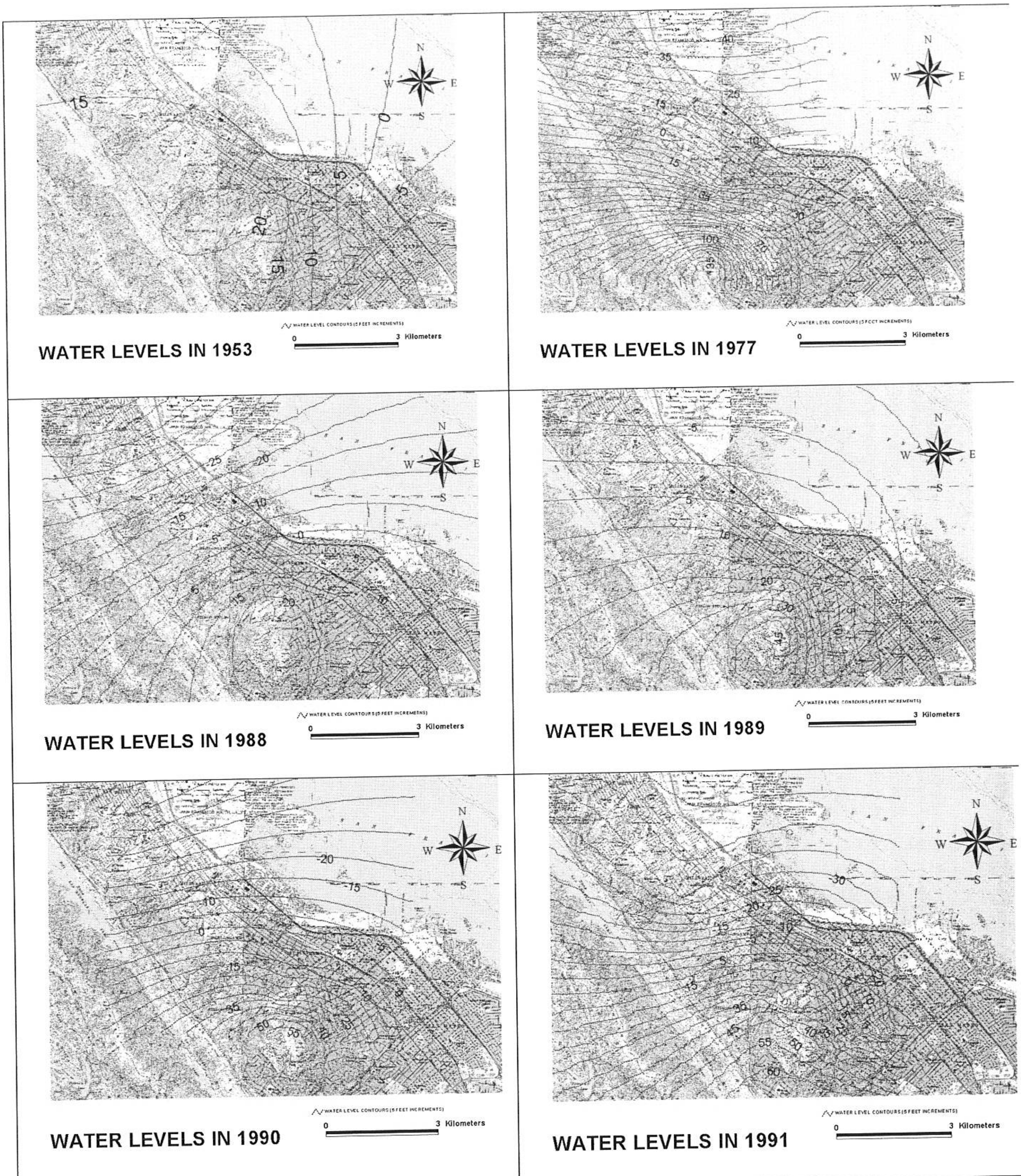


Figure 4.4: *Historical water level contours in the area from Millbrae to San Mateo. The contours show the presence of a groundwater high close to the area between Hillsborough and Coyote Point.*

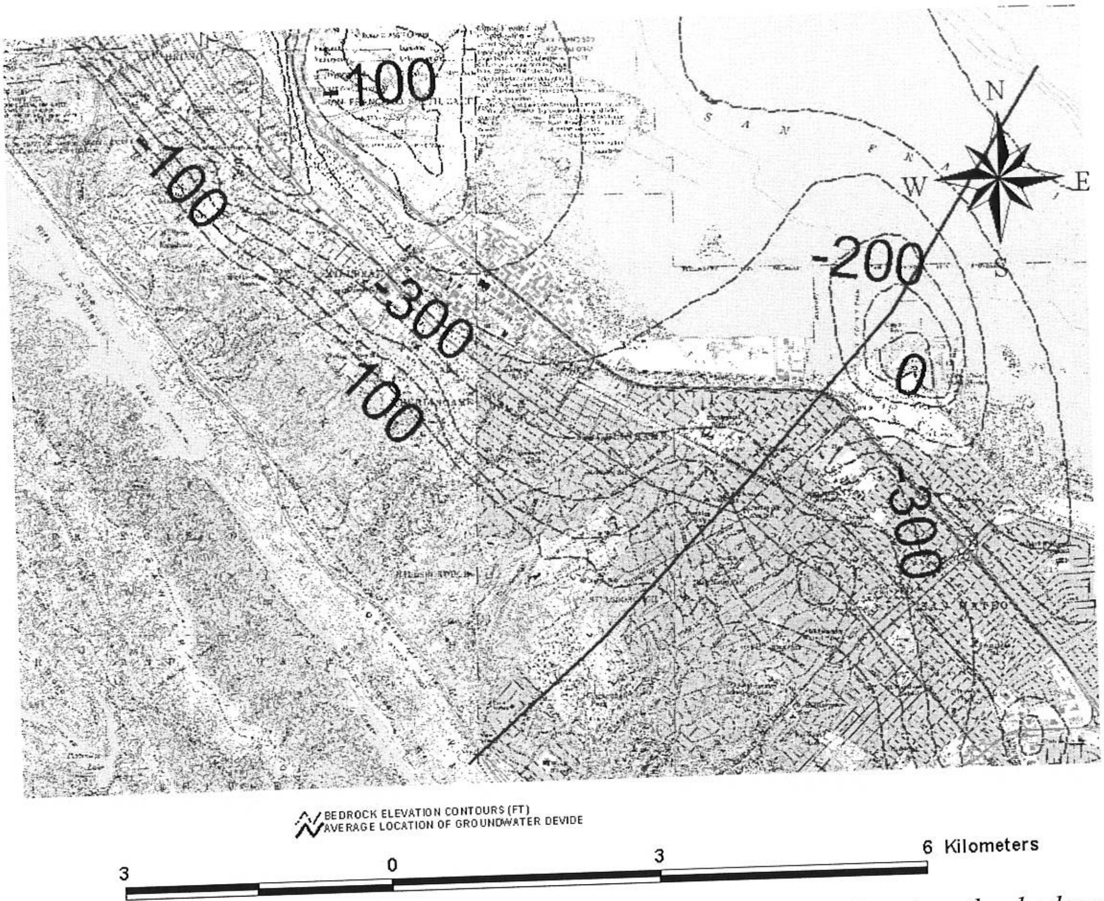


Figure 4.5: *Map for the area between Millbrae and San Mateo showing the bedrock elevation in the area and the average groundwater level high location. Both the local bedrock high and the groundwater level high seem to overlap*

4.3.2 Hydrostratigraphic units:

From all the four cross sections (Plates A, B, C and D) some general characteristics can be observed in these cross sections. The area between the San Andreas and Serra faults is highly folded. In contrast, the sediments east of the Serra fault are almost horizontally layered. At times, they can be tilted up to 5° to the northeast and, locally, some dragging effects can be observed immediately east of the Serra fault.

Furthermore, the degree of folding of the Merced Formation and the amount of offset along the Serra fault seems to be greater in the southeast than in the northwest. In the southeast (between San Bruno and Hillsborough) the Serra fault is not composed of a single strand but of two to three strands forming a thrust zone parallel to the San Andreas fault. In Burlingame and Hillsborough the Merced Formation occurs as erosive lenses between individual strands of the Serra fault. Franciscan Group rocks can be found overriding Merced Formation in this area. In Millbrae and San Bruno the Merced Formation is highly folded and although most of the offset along the different strands of the Serra fault occurs within the Merced Formation, locally Franciscan Group rocks can still be found overriding Merced Formation. Further northwest in the Westborough District one major strand of the Serra fault is still noticeable. There is no evidence for other strands of the Serra fault to come to the surface. However, synclines and anticlines are observed and these line up with strands of the Serra fault further southeast. Finally, in Daly City the main strand of the Serra fault can be observed to the northwest but mostly its location is only suggested by a syncline. Other synclines and anticlines just west of the San Andreas Fault are also present.

East of the Serra fault the sediments of the Merced Formation are mostly horizontally layered. A precise correlation between these sediments with the sequences described by Clifton and Hunter (1989, 1991, 1999) along the bluffs in Daly City is difficult. However, some general aspects can be identified based on previous findings by Potter (1999) and differences in water quality with depth. Potter (1999) determined that the mineral composition of the water from wells in San Bruno is representative of water that has been in contact with sediments derived from the Sierra Nevada. Such sediments are found in the upper part of the Merced Formation (sequences P through Y) and the Colma Formation (sequence Z). Therefore, at least to a depth of 200 meters below sea level, which is roughly the depth of the deepest wells in Daly City, South San Francisco and San Bruno east of the Serra fault sequences P through Z are present. Among these sequences, the ones, which have high clay content, are sequences Q_1, R_1, $S_{1 \text{ and } 2}$, W and Z. Although, sequence Z (Colma Formation) is composed mainly of sand along the coastal bluffs in Daly City (Clifton and Hunter 1989, 1991, 1999) Hochstetler (1973) described the Colma Formation in the area from Daly City to South San Francisco as containing higher clay content. All cross sections show the presence of clay layers. Although these clay layers are not clearly continuous in all of the cross sections, five general zones with higher clay content can be identified. These zones could be equivalent from top to bottom to sequences Z, W, $S_{1 \text{ and } 2}$, R_1 and Q_1.

Despite the clay layers not being continuous in the cross sections water quality parameters provide clues supporting the presence of different hydrostratigraphic units. In particular, chloride and nitrate data show drastic differences and unique trends. Table 4.1 shows chloride and nitrate concentrations for various wells in the Westside Basin. Nitrate values vary in the basin depending on local land use. To account for these land use differences the data in the table are presented by subareas based on geographic location. For the majority of the subareas a common observation is that the wells that have the shallowest top of screen show the lowest chloride concentration and the highest nitrate concentration. Reversibly, the wells with the deepest top of screen have the highest chloride concentration and the lowest nitrate concentrations. The increase of chloride concentration with depth could be related to pumping of connate water. The reduction in nitrate concentration is probably due to vertical travel time for infiltrating water to reach the lower water bearing zones. This is the case in the eastern part of the Golden Gate Park between Arboretum 5 and Elk Glenn wells, in the western part of the Golden Gate Park between the USGS Windmill wells and SL1, at the Zoo between Zoo 4 and Oceanside wells, in Daly City among Westlake, Lake Merced Country Club and DC10 wells (cross section B-B'; Plate B), in South San Francisco among SS 1-19, SS 1-20 and SS 1-21 wells (cross section C-C"; Plate C) and in San Bruno between SB16 and Vince's Shellfish wells.

This observation is not valid for wells located in close proximity to Lake Merced. Evaporative effects that increase chloride concentrations and biological processes that reduce nitrate concentrations occur in the lake. Increased chloride and reduced nitrate concentrations can be observed in wells around Lake Merced. In some other subareas, however, although nitrate concentrations decrease with depth, chloride concentrations also decrease with depth. This is the case among wells in Colma, the central part of Daly City and parts of San Bruno. It is possible, that pumping effects in those areas have not been drastic enough to cause connate water to be pumped into the wells. Furthermore, in Hillsborough no general trend in both nitrate and chloride concentrations can be observed. This could be due to different factors like differences in land use from property to property and amount of pumping activity at the wells. Nevertheless, the most decisive factor is likely the presence of back flow prevention devices at these wells. Back flow prevention devices are set at pipes that connect a well to a water main. They are designed to avoid backflow of well water to enter the water mains, which carry municipal water. However, they do not prevent municipal water from entering a well. Therefore, at times when the water pressure in a water main is high, it is possible that municipal water, which is chlorinated, enters a well. Over time, if municipal water recharges the local aquifer the chemistry of the aquifer surrounding a well will change. This assumption is supported by the presence of low concentrations of trihalomethanes (THM) in these wells. THM at low concentrations are common in municipal drinking water that is chlorinated.

AREA	WELL NAME	TOTAL DEPTH (m)	WELL HEAD ELEVATION (m)	TOP OF SCREEN ELEVATION (m)	BOTTOM OF SCREEN ELEVATION (m)	Cl 05-00	NO3 05-00	Cl 04-01	NO3 04-01	Cl 10-01	NO3 10-01
GG-E	Arboretum 5	79.3	63.31	57.2	-12.9	31.80	49.00	29	77		
GG-E	Elk Glenn	112.8	51.6	-0.2	-62.5	38.40	49.20	41	55	40	49
GG-W	SL-1	51.2	27.1	-12.0	-21.2			31	32		
GG-W	USGS Windmill SS		8.3	-0.8	-6.9			94	35		
GG-W	USGS Windmill SM		8.3	-27.7	-33.8			43	29		
GG-W	USGS Windmill SD		8.2	-105.2	-109.8	89.10	0.93	91	< 0.2		
GG-W	Windmill NE	47.6	10.1			41.70	27.70	44	28		
GG-W	Windmill South	70.1	7.6					41	38	42	38
SSET	West Sunset Playground	149.7	22.9	-22.8	-77.7	20.20	0.00	23	< 0.2		
LM	Edgewood School	65.2	45.5	30.2	-19.8	28.40	33.80	30	44	31	46
LM	LMMW5S	76.2	12.9	-6.9	-13.0			80	22		
LM	LMMW1S	23.2	14.9	-0.3	-6.4			130	37		
LM	LMMW 4S		10.8	-18.1	-24.2			76	95		
ZOO	Oceanside	148.2	7.9	-37.8	-83.5	64.30	0.14	82	< 0.2		
ZOO	Zoo4		3.8	-8.4	-63.3	43.40	33.10				
ZOO	Zoo 5		3.5							53	23
LM	LMMW2D	29.0	10.6	-41.2	-47.3	39.10	3.04	66	0.3		
LM	LMMW2S	62.5	10.4	-10.9	-17.0			76	2.2		
LM	LMMW3S	29.0	9.4	-12.0	-18.1			100	0.8		
LM	LMMW3D	76.8	9.4	-45.4	-51.5	73.20	0.64	91	< 0.2		
LM	LMMW6D	85.4	10.9	-59.2	-65.3	27.80	1.62	56	< 0.2		
TB	Fort Funston S		56.9	-19.4	-25.8			33	< 0.2		
TB	Fort Funston M		56.9	-117.5	-123.6			12	0.7		
TB	Fort Funston D		56.9	-385.2	-397.4			20	0.4		
LM	Olympic Country Club 9	210.4	18.8	-42.2	-142.8					98	2
LM	San Francisco Golf Club 1	167.4	42.4	-67.3	-122.2	49.70	3.43	53	3.9		
DC-N	Lake Merced Country Club		48.2	-40.0		54.30	33.10	69	40	56	36
DC-N	Westlake	214.0	34.1	-69.5	-173.2	108.00	31.60	110	28	120	27
DC-N	DC 10		69.8	-20.0		50.50	40.60				
DC-C	Jefferson Well	213.4	63.4	-78.4	-110.4	55.80	11.60	56	11	55	11
DC-C	Vale Well	213.4	53.4	-74.7	-157.0	65.70	33.40	70	33	75	36
DC-C	DC 04		40.5	-38.8	-105.8	65.20	61.00				
DC-S	A St	179.9	54.3	9.1	-107.9	71.90	53.50	73	57	72	63

AREA	WELL NAME	TOTAL DEPTH (m)	WELL HEAD ELEVATION	TOP OF SCREEN ELEVATION (m)	BOTTOM OF SCREEN ELEVATION (m)	Cl 05-00	NO3 05-00	Cl 04-01	NO3 04-01	Cl 10-01	NO3 10-01
CL	Home of Peace		40.0	-28.3	-106.3	77.60	85.40				
CL	Hills of Eternity		43.6	-15.5	-46.0	77.50	98.60				
CL	Holy Cross Cemetery 1	213.4	27.4	-84.8	-176.2	57.00	41.30				
CL	Cypress Lawn Cemetery 2	182.9	42.1	-16.2	-136.3	69.10	46.90	80	58		
SS	SS 1-14	166.8	11.8	-9.3	-140.7	120.00	38.00	120	36	130	60
SS	SS 1-15	164.3	10.2	-26.4	-152.9	125.00	32.00				
SS	SS 1-17	145.7	9.0	-36.7	-131.2						
SS	SS 1-18	163.1	12.8	-57.6	-163.4	91.00	69.00			59	62
SS	SS 1-19	161.0	8.6	-57.3	-152.4	121.00	31.00	120	33	130	37
SS	SS 1-20	183.5	16.6	-99.2	-160.2			160	4.1	160	7
SS	SS 1-21	189.0	12.8	-100.0	-164.0			160	< 0.2		
SS	California Golf Club 5		15.2	-64.1	-160.4	103.00	6.34			110	6
SB	SB 16	182.9	13.7	-89.9	-159.5	107.00	0.00	110	0.3	110	0.3
SB	Vince's Shellfish		6.1	-39.6	-131.1	66.20	1.38	76	1.1	75	1
SB	SB 15	162.8	30.5	-61.0	-122.0	98.00	8.50			110	3
SB	SB 17	157.0	3.0	-88.4	-154.0	66.00	3.50	59	3.9	58	4
SB	SB 18	150.9	16.8	-62.5	-123.5	39.00	5.80	71	5.9	69	6
SB	Greenhills Country Club 5	94.8	53.1	5.5	-34.1	101.00	16.00				
MI	852 Hawthorne	88.4	26.6	-16.1	-58.8	28.70	5.85	31	3.2		
HB	Burlingame Country Club 6	61.0	39.9	21.6	-14.9	67.50	1.29				
HB	1700 Floribunda	33.5	16.8	10.7	-16.8	4.91	0.67				
HB	25 New Place Rd	67.1	48.78	18.3	-6.1	9.40	3.96				
HB	812 Irwin Dr	50.3	28.35	16.2	-14.3	161.00	8.63				
HB	510 Eucalyptus	91.5	38.11	13.7	-22.9	9.14	3.89				
HB	101 New place Rd	45.7	73.17	51.8	33.5	44.00	2.90				
HB	1100 Jackling Dr	22.9	33.54	27.4	15.2	69.40	33.40				

Table 4.1: *Chloride and nitrate concentrations for Westside Basin wells. GG-E stands for eastern part of the Golden Gate Park, GG-W for western part of the Golden Gate Park, SSET for Sunset, LM for Lake Merced, ZOO for the Zoo are, TB for Thornton Beach, DC-N for northern part of Daly City, DC-C for central part of Daly City, DC-S for southern part of Daly City, CL for Colma, SS for South San Francisco, SB for San Bruno and HB for Hillsborough.*

In 2001, Moran, J. (written communication, 2001) collected water samples from 4 wells in the Westside Basin (Jefferson well and Vale well in Daly City, SB15 in San Bruno, and 852 Hawthorne in Millbrae) and analyzed the samples for tritium and helium

(^{4}He) isotopes. The 852 Hawthorne well has a shallower top of screen interval than all the other three wells (Table 4.1). But for this well the analytical results indicate higher tritium concentration and very low ^{4}He concentrations. However, tritium is negligible in all other wells; however, a substantial amount of ^{4}He is present. The contrasting concentrations in tritium and ^{4}He point to different sources of water from which well 852 Hawthorne draws water. Furthermore, the concentrations indicate that the water pumped at well 852 Hawthorne was recently recharged, while the water at Jefferson, Vale and SB15 wells is very old. The estimated age of the water at Jefferson and Vale wells is 100 years, while at SB15 is 700 years.

Jefferson and Vale wells are located south of DC10, a well shown on cross section B-B' (Plate B). Their screen interval is also similar to that of well DC10. Therefore, well DC10 could be drawing water from the same water-bearing unit as Jefferson and Vale wells. As described above, well DC10 (Table 4.1) has a relatively low nitrate concentration. Nitrate, however, is mostly introduced to groundwater through human activity. This would mean that the nitrate concentrations currently found in the water in well DC10 was introduced to the ground about 100 years ago. Historical records (Daly City Online, 2000, 2001) indicate that about 100 years ago the land use in Daly City was mainly agricultural. There were many dairy, artichoke and hog farms in the area. It is, therefore, conceivable, that fertilizers from the artichoke farms and manure from the dairy and hog farms contributed the nitrates currently observed in the deeper water bearing zones of the Westside Basin.

Chapter 5

CONCLUSION

In this thesis two basic questions on characteristics of the Westside Basin have been addressed, the identification of the southern boundary of the Westside Basin and a tentative correlation between the sequences of the Merced Formation along the coastal bluffs in Daly City and the Merced formation deposits east of the Serra fault.

Historical water level data has been interpolated for the area between San Bruno and San Mateo. The resultant potentiometric maps seem to indicate a groundwater high stretching in a southwest-northeast direction from the central part of Hillsborough to Coyote Point. This potentiometric high mimics a subsurface bedrock high in this area. Therefore, it seems plausible to adopt this area as the southern boundary of the Westside Basin. The knowledge of this groundwater basin divide will help improve future groundwater basin management for both the Westside Basin and the neighboring San Mateo Plain by local authorities. It will also improve future groundwater models and allow one to more adequately estimate the safe yield of the basin.

The review of available geologic data and reports allowed a better understanding of the stratigraphic and structural characteristics of the basin. It showed that (i) the Westside Basin is folded west of the Serra fault and essentially horizontally layered east of the fault and (ii) that the Colma Formation is essentially thinner than previously thought and is mostly composed of clayey and silty sand across most of the San Francisco Peninsula. This knowledge has been incorporated into cross sections developed for the basin. These cross sections resulted in identifying different zones of higher permeability (mostly sand) separated by zones of lower permeability (mostly silt and clay). Thus, wells screened in different permeability zones show different potentiometric surface.

Based on these stratigraphic characteristics of the Westside Basin east of the Serra fault can be subdivided into different hydrostratigraphic units. A hydrostratigraphic unit, as defined by Seaber (1988) is "a body of rock distinguished and characterized by its porosity and permeability". It forms a distinguished hydrologic unit with respect to groundwater flow (Maxey 1964). Therefore, the upper part of the Westside Basin can be subdivided in the following hydrostratigraphic units:

HS1: Young Bay Muds found only along the San Francisco Bay;

HS2: Alluvium and San Dunes overlying the Colma Formation;

HS3: Colma Formation (Sequence Z);

HS4: Sequence X and Y;

HS5: Sequence W;

HS6a: Sequence U and V;

HS6b: Sequence T

HS7: Sequence S;

HS8: Sequence $R_{2-4;}$

HS9: Sequence $R_{1,2}$.

HS10: Sequence Q_1

HS11: Sequence Q_2,

where HS1, HS3, HS5, HS7, HS9 and HS11 are the low permeability units and HS2, HS4, HS6, HS8 and HS10 the higher permeability units. HS6 has been subdivided in two, in order to reflect the unconformity found between sequences T and U in the Merced Formation.

There are other hydrostratigraphic units composed of sequence P and lower. However, because of the limited number of available well logs and limit in depth of wells drilled in the Westside Basin these lower hydrostratigraphic units could not be identified.

Geochemical data supports the subdivision of these hydrostratigraphic units. While, in many parts of the Westside Basin, chloride concentrations increase with depth, nitrate concentrations decrease with depth. The higher chloride concentrations found in lower hydrostratigraphic units could be correlated with the presence of connate water. The lower nitrate concentrations are most likely due to traveling time for vertical percolation of water to the deeper hydrostratigraphic units. The presence of the different clay layers increases the traveling time. Isotopic data collected by Moran, J. (written communication, 2001) further corroborates this interpretation. While the upper hydrostratigraphic units show elevated tritium and minimal 4He concentrations, typical of recently recharged water, the lower hydrostratigraphic units contain minimal tritium and show substantial amounts in 4He, typical of water that has been in the subsurface for a very long time. The age of water samples collected from wells screened in the lower hydrostratigraphic units in Daly City has an average of 100 years; those samples taken from equivalent wells in San Bruno are on average 700 years old (Moran, J., written communication 2001). Historical land use data for Daly City (Daly City Online, 2000, 2001) indicate the presence of dairy, artichoke and hog farms in the area starting in the second half of the 19th century. These could be a likely sources for the nitrate concentrations found in the Westside Basin. Nitrate that entered the groundwater basin around the turn of the 19th to the 20th century slowly percolated through the different sand and clay layers and is now showing up in water in the lower hydrostratigraphic units.

This proposed subdivision of the Westside Basin into different hydrostratigraphic units will also improve the future groundwater management decisions of the basin. Knowing where to expect zones of higher permeability and what their what their water quality parameters might be is extremely useful for future groundwater exploration. Screen intervals for future wells may be designed in such a manner as to maximize productivity and water quality. Undesired water bearing zones containing higher chloride or nitrate concentrations can, therefore, be sealed off.

The majority of wells found in the Westside Basin are screened across different water bearing zones. It is still unknown how much water each of these units contains and what their individual water quality is. The analytical results for most current wells represents a mixture of different water bearing zones. Future wells that might be installed in the Westside Basin and where each is screened within one water-bearing zone might provide clues to better differentiate the various hydrostratigraphic units and corroborate the proposed subdivision. Alternatively, packered water samples could be collected at different depths from existing wells.

For any future well, the mineralogical analysis of drill cuttings rather then geochemical analysis of the well's water can further pinpoint the boundary between the upper and lower Merced Formation in the center of the Westside Basin. Furthermore, placing some wells west of the Serra fault might provide better stratigraphic control for cross sections and allow a more precise determination if the folding of the Merced Formation west of the Serra fault forms a natural barrier against salt water intrusion from the Pacific Ocean.

Bibliography:

ABAG (1995): Description of land use classification categories. Association of Bay Area Governments (ABAG), Oakland, CA.

Addicott, W.O. (1968): Mid-Tertiary zoogeographic and Paleogeographic discontinuities across the San Andreas fault, California, in Proceedings of Conference on Geologic Problems of San Andreas fault system, edited by W.R. Dickinson and Arthur Grantz. Stanford University Publications, Geological Sciences, volume 11, pages 144-165.

Addicott, W.O. (1969): Late Pleistocene Mollusks from Northwest Santa Cruz County, California, and their Paleogeographic Significance; in Proceedings, California Academy of Sciences 4th Series, volume 37, number 3, p. 57-93.

AGS, Inc. (1995): San Francisco Zoo Infrastructure Master Plan, Job # 920801, prepared for the San Francisco Department of Public Works.

Alexander, M. (1991): Introduction to Soil Microbiology; Krieger Publishing Company; Malabar, Florida.

Alt, D. and Hyndman, D.W. (1975): Roadside Geology of Northern California

Alt, D. and Hyndman, D.W. (2000): Roadside Geology of Northern and Central Califorina.

Alvarez, W.O., Kent, D.V., Premoli Silva, I., Schweikert, R.A., and Larson, R.A. (1980): Franciscan Limestone deposited at 17° South Paleolatitude; in: Geological Society of America Bulletin, v. 91, no. 8, pt. I, p. 476-484.

Applied Consultants (1991): Report on the Daly City Groundwater Investigation and Model Study; prepared for City of Daly City, CA, 153 p.

Argus, D.F. and Gordon, R.G. (1990): Pacific-North American Plate Motion from very Long Baseline Interferometry Compared with Motion Inferred from Magnetic Anomalies, Transform Faults and Earthquake Slip Vectors; in Journal of Geophysical Research, volume 95, number B11, p. 1014, 15p.

Arnold, R. (1906): The Tertiary and Quaternary Pecten of California; US Geological Survey Professional Paper 47, 264 p.

Ashley (1895): The Neocene Stratigraphy of the Santa Cruz Mountains; Stanford University Publications in Geology and Paleontology, p. 273-367.

Atwater, B.F., Hedel, C.W., Helley, E.J. (1977): Late Quaternary Depositional History, Holocene Sea-Level Changes, and Vertical Crustal Movement, Southern San Francisco Bay, California; US Geological Survey Professional Paper 1014, 15 pages.

Aydin and Page (1984):

Ayers, R.S. and Westcost, D.W. (1985): Water Quality for Agriculture; Food and Agriculture Organization of the United Nations – Irrigation and Drainage Paper No. 29, Rev. 1; Rome.

Bailey, E.H., Irwin, W.P. and Jones, D.L. (1964): Franciscan and related rocks, and their significance in the geology of western Califorina: Califorina Division of Mines and Geology Bulletin 183, 177p.

Bailey, W. (1938): San Andreas Rift, California; Journal of Geology, Volume 46, Number 6, pages 793-827.

Barr, J (1999): Northern Continuation of the Serra Fault to Southwest San Francisco: Constraints on Uplift rates and Style of Deformation on the San Francisco Peninsula; Senior Thesis at San Francisco State University.

Baywood Group (2000): Aquifer Test Groundwater Levels; e-mail sent to Rogge, E. H., San Mateo County Environmental Health Division, by Enkeboll, R., Baywood Group; May 01, 2000.

Bennett, J.H. (1980): Geodimeter Measurements of Strain and Slip along the Northern San Andreas Fault system; in Streitz, R. and Sherburne, R., editors: studies on the San Andreas Fault Zone in Northern California; California Division of mines and Geology Special Report 140, p. 99-109.

Blake, M.C. Jr., Howell, D.C. and Jones, D.L. (1982): Preliminary Tectonostratigraphic map of California; United States Geological Survey Open-File Report 82-593, 9 pages, 3 maps, scale 1:750,000.

Blake, M.C. Jr., Howell, D.C. and Jayko, A.S. (1984): Tectonostratigraphic terranes of the San Francisco Bay Region; in: Franciscan Geology of Northern California, Volume 43, edited by Blake, M.C., pp. 5-22; Soc. Econ. Paleontol. Mineral., Pacific Section.

Blake, M.C. Jr., Graymer, R.W. and Jones, D.L. (2000): Geologic Map and Database of Parts of Marin, San Francisco, Alameda, Contra Costa and Sonoma Counties, California; United States Geological Survey Miscellaneous Field Studies MF-2337, Version 1.0.

Blake, W.P. (1858): Report of a geological reconnaissance in California; H. Bailliere, 290 Broadway, New York.

Bonilla, M.G. (1959): Geologic observations in the epicentral area of the San Francisco earthquake of March 22, 1957: in California Division of Mines, Special Report 57, p. 25-37.

Bonilla, M.G. (1960): Landslides in the San Francisco South Quadrangle, California; United States Geological Survey Open File Report.

Bonilla, M.G. (1964): Bedrock-surface map of the San Francisco South Quadrangle, California; US Geological Survey Miscellaneous Field Studies Map MF-334, scale 1:31,680.

Bonilla, M.G. (1965): Geologic Map of the San Francisco South Quadrangle, California; US Geological Survey Open-File Map 65-18, Scale 1:20,000.

Bonilla, M.G. (1971): Preliminary Geologic Map of the San Francisco South Quadrangle and part of the Hunter's Point Quadrangle, Califorina; US Geological Survey Miscellaneous Field Studies Map MF-311, 2 sheets, scale 1:24,000.

Bonilla, M.G. (1994): Serra Fault Zone, San Francisco Peninsula, California (abs.); in: EOS, Transactions of the American Geophysical Union, Volume 75, p. 681.

Bonilla, M.G. (1998): Preliminary Geologic Map of the San Francisco South 7.5 Quadrangle and Part of the Hunters Point 7.5 Quadrangle, San Francisco Bay Area, California: A digital database; United States Geological Survey Open-File Report 98-0354.

Bonilla, M.G., Jachens, R.C., Jayko, A.S., Wentworth, C.M. and McGarr, A.F. (2000): The Demise of the San Bruno Fault; in: California Geology, Volume 53, Number 2, p. 4-19.

Boone, Cook and Associates (1987); Study for alternative sources of supply for irrigation water at the Golden Gate National Cemetery, San Bruno, CA; 39 p.

Borgman G.N., and Vardy, P. (1969): Mussel Rock Landslide in 1969: Field Trip for National Meeting of Association of Engineering Geologists, San Francisco, p. E-3 and E-4.

Brabb, E.E., Pampeyan, E.H. and Bonilla, M.G. (1972): Landslide Susceptibility in San Mateo County, California; United States Geological Survey Miscellaneous Field Studies Map MF-360.

Brabb, E.E. and Hanna, W.F. (1979): Map showing Aeromagnetic anomalies, faults, earthquake epicenters, and igneous rocks in the southern San Francisco Bay region, California; United States Geological Survey Geophysical Investigations Map GP-932, 3 sheets, scale 1:125,000.

Brabb, E.E. and Pampeyan, E.H. (1983): Geologic Map of San Mateo County, Califorina: US Geological Survey Miscellaneous Investigations Map I-1257-A, scale 1:62,500.

Brabb, E.E. and Olson, J.A (1986): Map showing faults and earthquake epicenters in San Mateo County, California; United States Geologic Survey Miscellaneous Investigations Map I-12570F, scale 1:62,500.

Brabb, E.E., Graymer, R.W and Jones, D.L. (1998): Geology of the onshore part of San Mateo County, California: A digital database; US Geological Survey Open-File Report 98-137.

Bruun, P (1962): Sea level rise as a cause of shoreline erosion; American Association of Civil Engineers Proceedings; Journal of Waterways and Harbors, volume 88, p.117-130.

Burns and McDonnell (2001): oral communication on the geology of the San Francisco International Airport.

Burns and McDonnell (2002): Building 84; Bedrock Investigation Report; San Francisco Maintenance Center; San Francisco International Airport, California; prepared for United Airlines.

Caldwell-Gonzalez-Kennedy-Tudor (1982): Bayside Facilities Plan, expanded Geotechnical Investigation, Geotechnical Reference Report: San Francisco, California; 127 p.

California Division of Highways (1959): San Francisco Earthquake of 1957; Special Report Number 57.

California Water Service (1923-1973): Well logs for South San Francisco and San Mateo facilities wells.

CH2MHILL (1989): Technical Memorandum for Oceanside Water Pollution Control Plant Groundwater Development Study; Report to San Francisco Clean Water Program, 35 p.

CH2MHILL (1994): Technical Memorandum 8, Summary of Results, Westside Basin Field Investigation; prepared for San Francisco Water Department; 13 p.

CH2MHILL (1996): Revised Draft for Technical Memorandum 4 (1993), Groundwater Resources; prepared for San Francisco Water Department; 36 p.

CH2MHILL (1997): Review Draft of Technical Memorandum 18, Westside Basin Groundwater Model; prepared for San Francisco Water Department; 16 p.

Chiocci, F.L. and Clifton, H.E. (1992): Gravel filled gutter casts in nearshore facies – indicators of ancient shoreline trend; in: Osborne, R.H., editors: Contributions in Marine

Geology Honoring Francis Parker Shepard: Society of Economic Paleontologists and Mineralogists Special Publication.

Christensen, M.N. (1966): Quaternary of California Coast Ranges; in: Bailey, E.H. (1966): Geology of Northern California; California Division of Mines and Geology Bulletin 190; p.305-313.

Clifton, H.E. and Stagg, J. (1986): Lithofacies in Part of the Merced Formation in the Sea Cliff Exposures between Thornton Beach and Woods Gulch, Daly City, California; US Geological Survey Open File Report 86-91.

Clifton, H. E. and Hunter, R. E. (1987): The Merced Formation and Related Beds: A Mile Thick Succession of Late Cenozoic Coastal and Shelf Deposits in the Sea cliffs of San Francisco, California; Geological Society of America Centennial Field Guide – Cordilleran Section p.257-262.

Clifton, H. E., Hunter, R. E. and Gardner, J.V. (1988): Analysis of Eustatic, Tectonic, and Sedimentologic Influences on Transgressive and Regressive Cycles in the Upper Cenozoic Merced Formation, San Francisco, California; in: Kleinspehn, K. L. and Paola, C., eds.: New Perspectives in Basin Analysis; Frontiers in Sedimentary Geology; Springer Verlag, p.109-128.

Clifton, H.E. (1989): The Merced Basin on the San Francisco Peninsula; in: Wahrhaftig, C. and Sloan, D., editors (1989): Geology of San Francisco and Vicinity: Field Trip Guidebook T 105, 28th International Geologic Congress, American Geophysical Union, Washington, D.C., p.32-33.

Clifton, H.E. and Hunter, R.E. (1991): Depositional and other features of the Merced Formation in Sea Cliff Exposures South of San Francisco, California; in: Sloan, D. and Wagner, D. (1991): Geologic Excursions in Northern California: San Francisco to Sierra Nevada; California Division of Mines and Geology; Special Publication 109, p. 35-44.

Clifton, H. E. and Hunter, R. E. (1999): Depositional and other features of the Merced Formation in Sea Cliff Exposures South of San Francisco, California; in: Geologic Field Trips in Northern California; Centennial Meeting of the Cordilleran Section of the Geological Society of America; Special Publication 119.

Cooper, A. (1973): Structure of the Continental Shelf West of San Francisco; Us Geological Survey Open-File Report 73-48, 72 p.

Cooper, J.G. (1888): Catalogue of California Fossils, in Seventh Annual Report State Mineralogist; California State Mining Bureau, p. 223-308.

Costa, J.E. and Baker, V.R. (1981): Surficial Geology, Building with Earth; John Wiley & Sons Publishing Company; ISBN 0-471-03229-8.

Cowan, D.S (1985): Structural styles in Mesozoic and Cenozoic mélanges in the western Cordillera of North America: Geological Society of America Bulletin, V. 96, no. 4, p. 451-462.

Cox-Whitsel, J. (1983): Daly City Landfill: A Case History; Master Thesis presented to the Faculty of the University of San Francisco.

Crandall, R. (1907): The Geology of the San Francisco Peninsula; American Philosophical Society Procedures, Volume 46, p. 3-58.

Crandall, R. (1908): Description of the San Francisco earthquake of 1906; in: Lawson, A.C. (1908): The California earthquake of April 18, 1906, Report of the State Earthquake Investigation Commission, in two volumes and atlas: Carnegie Institute Washington Publication 87, (v. 1 parts 1 and 2, Record of observations, p.1-451; v. II Mechanics of the earthquake, p.1-192; Atlas, 25 maps, 15 seismographs).

Cummings, J.C., Touring, R.M. and Brabb, E.E. (1962): Geology of the Northern Santa Cruz Mountains, California; in Geologic Guide to the Gas and Oil Fields of Northern California, Part II; California Division of mines and Geology Bulletin 181, p. 179-220.

Cummings, J.C. (1968): The Santa Clara Formation and Possible Post-Pliocene Slip on the San Andreas Fault in Central California; in Proceedings on the Conference on Geologic Problems of the San Andreas Fault System; edited by W.R. Dickinson and A. Grantz; Stanford University Publications in Geologic Science, volume 11, p.191-207.

Cummings, J.C. (1983): The Woodside Facies Santa Clara Formation and Late Quaternary Slip on the San Andreas Fault, San Mateo County, California (abs.); in Programs and Abstracts for the 58th Annual Meeting, Pacific Section, American Association of Petroleum Geologists, Society of Exploration Geophysicists, SEPM, Sacramento, California, p.82.

Daly City Online (2000): Wastewater Treatment and Disposal; http://www.ci.daly-city.ca.us/depts/Wwr/waste_treatment.htm

Daly City Online (2001): The History of Daly City; http://www.ci.daly-city.ca.us/about/history.htm

Dames and Moore (1979): Final Report, Geotechnical investigation, route selection study, Richmond Transport Service, San Francisco, California: San Francisco, Califorina, 57 p.

Davis, J.A., McKee, L.J., Leatherbarrow, J.E. and Daum, T.H: Contaminant Loads from Stormwater to Coastal Waters in the San Francisco Bay Region, Comparison to other Pathways and Recommended Approach for Future Evaluation; San Francisco Estuary Institute; http://www.sfei.org/rmp/reports/AB1429/AB1429_Final_wcover.pdf

Davis, S.N. (1969): Porosity and Permeability of Natural Materials, in DeWiest, R.J.M., editors, Flow through Porous Media; New York, Academic Press, p. 53-89.

Dibblee, T.W. (1966): Evidence for Cumulative Offset on the San Andreas Fault in Central and Northern California, California Division of Mines and Geology Bulletin 190, pages 375-384.

Dickinson, J.B. and Weed, S.B. (1989): Minerals in Soil Environments; 2nd edition; Soil Science Society of America, 1244 pp.

Eagle, H.E. and Squires, B.T. (1974): Report of Geotechnical Investigation of Road 04-SM-1 (Abandoned) at Thornton Bluffs; State of California, Department of Transportation, Division of Construction and Research, Transportation Laboratory.

Earth Investigation Consultants (1998): Preliminary Engineering Geologic Report for the Avalon Canyon, Daly City, California; prepared for the City of Daly City.

Elder, W.P. (1999): Mesozoic Molluscan Fossils from the Golden Gate Recreation Area and their Significance to Franciscan Terrane Reconstruction, San Francisco Bay Area, California; http://www.aqd.nps.gov/grd/geology/paleo/pub/grd3_3/goga1.htm

Elder, W.P. (2001): Geology of the Golden Gate Headlands; in: Stoffer, P.W. and Gordon, L.C. (eds.): Geology and Natural History of the San Francisco Bay Area: A Field-Trip Guidebook; United States Geological Survey Bulletin 2188, pages 61-86.

Ellen, S.D. and Wentworth, C.M. (1995): Hillside Materials and Slopes of the San Francisco Bay Region, California; United States Geological Survey Professional Paper 1357.

Ellis, W.C. (1983): Hydrogeologic Report for the City of San Bruno, Water System Master Plan.

Ellis, W.C. (1989): Well Site Evaluation for Future Development; elaborated for the City of San Bruno.

Fahy, N.E. (1974): Origin of Lake Merced; in: California Geology, Volume 27 (8) p. 171-174.

Finlayson, D.J., Hansen, W.R., Ford, R.S., Scott, R.G. and Vantine, J.V. (1967): Evaluation of Groundwater Resources, South Bay [California]. California Department of Water Resources Bulletin 118-1, 153 pages.

Fio, J. L. and Leighton, D. A. (1995): Geohydrologic Framework, Historical Development of the Groundwater System, and General Hydrologic and Water Quality Conditions in 1990, South San Francisco Bay an Peninsula Area, California; US Geological Survey; OF Report 94-357; 46 p.

Fio, J. L. (2000): Personal communication on historical groundwater readings in wells around Lake Merced.

Flynn, D.B. (1963): The San Benito-Waltham Canyon Trough – possible oil province?; in Guidebook to the geology of Salinas Valley and the San Andreas fault; in American Association of Petroleum Geologists (Guidebook) Pacific Section; AAPG-SEPM Annual Field Trip, p. 27-33.

Freeze, R.A., and Cherry, J.A. (1979): Groundwater; Englewood Cliffs, New Jersey, Prentice Hall, 604 p.

Galehouse, J.S. (1967): Provenance of Paleocurrents of the Paso Robles Formation, California; geological Society of America Bulletin, volume 78, number 8, pages 951-978.

GEI Consultants (1998): Geotechnical Investigation Report on the Avalon Repairs, City of Daly City, California; submitted to the City of Daly City, Department of Public Works.

GEI Consultants (1999): Geotechnical Investigation Data Report, Westline Drive Landslide, City of Daly City (file number 99060).

Geo/Resources Consultants, Inc. (1991): Groundwater Assessment and Drought Response for Golden Gate park San Francisco, California; prepared for City and county of San Francisco; 27 p.

Geo/Resource Consultants, Inc. (1993): Draft Report, Lake Merced Water Resource Planning Study, San Francisco, California; Prepared for San Francisco Water Department.

Gilbert, N.J. (1969): Chronology of Post-Tuscan Volcanism in the Manton Area, California; Unpublished Master of Science Dissertation; University of California, Berkeley.

Glen, W. (1959): Pliocene and Pleistocene of the Western Part of the San Francisco Peninsula; University of California Publications, Department of Geological Sciences Bulletin, Volume 36, number 2, pages 147-198, plates 15-17.

Grant, U.S, IV, and Gale, H.R. (1931): Catalogue of the marine Pliocene and Pleistocene Mollusca of California; San Diego Society of Natural History, Volume 1, p.7-1036.

Guidetti, J.R. & Schaefer, C.F. (1995): Groundwater Investigation and Wellhead Protection the Greater San Bruno Area; Final Report of Bachelor Thesis; San Mateo County Environmental Health Service Division.

Hall, N.T. (1965): Petrology of the Type Merced Group, San Francisco Peninsula, Califorina; Master Thesis at the University of California, Berkeley.

Hall, N.T. (1966): Late Cenozoic Stratigraphy between Mussel Rock and Fleishhacker Zoo, San Francisco Peninsula: California Division of Mines and Geology, Mineral Information Services, volume 19, number 11, p. S22-S25.

Hall, N.T. (1984): Holocene History of the San Andreas Fault between Crystal Springs Reservoir and San Andreas Dam, California; in Seismological Society of America Bulletin, Volume 74, pages 281-299.

Hall, N.T., Wright, R.H. and Clahan, K.B. (1999): Paleoseismic Studies on the San Francisco Peninsula Segment of the San Andreas Fault Zone near Woodside, California; in Journal of Geophysical Research, Volume 104, Number B10, pp. 23,215-23,236.

Harding Lawson Associates (1976a): Westside Transport Soil Investigation Phase 1; report prepared for Department of Public Works, Bureau of Engineering, Job Number 2047,060.04, 113 pages.

Harding Lawson Associates (1976b): Geotechnical Investigation, Westside Transport Project, Pump Station and Force Mains: San Francisco, California; Report prepared for Kennedy Engineers, Inc., 106 p.

Harding Lawson Associates (1977): Westside Transport, Geotechnical Investigation, Pump Station at Fleishhacker Pool near Sloat Blvd., San Francisco, California, Report prepared for Kennedy Engineers, Inc., 66 p.

Harsh, P.W. (1977): Alinement array measurements on the San Andreas Fault in Northern California and their tectonic significance (abstract); in Geological Society of America Abstracts with Programs, volume 9, number 4.

Hart, E.W. (1966): Shell deposits of southern San Francisco Bay; California Division of Mines and Geology Mineral Information Services, volume 19, number 3, p.41-45.

Hay, O.P (1927): The Pleistocene of the western Region of North America and its Vertebrate Animals; in Carnegie Institution of Washington, Publication Number 322B, 346p., 12plates.

Heath, R.C. (1987): Basic Groundwater Hydrology; United States Geological Survey Water Supply Paper 2220, 84 p.

Helley, E.J., Lajoie, K.R., Spangle, W.E. and Blaire, M.L. (1979): Flatland deposits of the San Francisco Bay region, California; their geology and engineering properties, and their importance to comprehensive planning: US geological Survey Professional Paper 943, 88p.

Hem, J.D.(1985): Study and Interpretation of Chemical Characteristics of Natural Water; United States Geological Survey Water-Supply Paper 2254; United States Government Printing Office, 263 pp.

Hem, J.D. (1992): Study and Interpretation of the Chemical Characteristics of Natural Water; third edition; United States Geological Survey Water-Supply Paper 2254.

The Hendrix Group (1998): Crevice Corrosion of Nickel-Based Alloys in Seawater; www.hghouston.com/n032298.html .

Hengesh, J.V. and Wakabayashi, J. (1995): Dextral Translation and Progressive Emergence of the Pleistocene Merced Basin and Implications for Timing of Initiation of the San Francisco Peninsula Segment of the San Andreas Fault; in: Recent Geologic Studies in the San Francisco Bay Area, volume 76, edited by E.M. Sangines, D.W. Anderson, and A.V. Buising, pp. 47-54, Society of Economic Paleontologists and Mineralogists, Pacific Section; Los Angeles, California.

Hensolt, W.H. and Brabb, E.E. (1990): Maps showing Elevation of Bedrock and Implications for design of Engineered Structures to Withstand Earthquake Shaking in San Mateo County, California; United States Geological Survey Open-File Report 90-496.

Higgins, C.G. (1961): San Andreas Fault North of San Francisco, California; Geological Society of America Bulletin, Volume 72, p. 51-68.

Hill, M.L. and Dibblee Jr., T.W. (1953): San Andreas, Garlock and Big Pine Faults, California – A Study of the Character, History, and Tectonic Significance of Their Displacements. Geological Society of America, Volume 64, Number 4, pages 443-458.

Hochstetler, L.H. (1973): The Stratigraphy and Distribution of the Colma Formation, San Francisco, California; Master of Science in Geology Thesis at the University of Califorina, Berkeley.

Howard, A.D. (1951): Development of the Landscape of the San Francisco Bay Counties. California Division of Mines and Geology Bulletin 154, pages 95-106.

Hunter, R.E. & Clifton, H.E. (1982): Description of Beds Exposed at Fort Funston, Golden Gate National Recreation Area, Northwestern San Francisco Peninsula, California; USGS Open-File Report 82-1055.

Hunter, R.E., Clifton, H.E., Hall, N.T., Csaszar, G. Richmond, B.M. & Chin, J.L. (1984): Pliocene and Pleistocene Coastal and shelf Deposits of the Merced Formation and Associated Beds, Northwest San Francisco Peninsula, CA; in: Society of Paleontologists and Mineralogists Field Trip Guidebook 3, 1984 Midyear Meeting, pp. 1-29.

Ingram, B.L. and Ingle, J.C. (1998): Strontium Isotope Ages of the Marine Merced Formation, near San Francisco, California; in: Quaternary Research 50, p.194-199.

Jacobs Associates (1999): Westline Drive Site Study, Daly City, California.

Jachens, R. C., Roberts, C.W., Zoback, M.L. (1996): Total offset and right-stepping geometry of the San Francisco Peninsula Segment of the San Andreas Fault, California, defined by Aeromagnetic anomalies (abstract); EOS Transactions, American Geophysical Union, volume 77 (46), Fall Meeting Suppl., F742.

Jones, D.L. (1992): Tectonics of a Transgressive Plate Boundary: A New Paradigm for Central California Coast Ranges; in Borchardt, G., Hirschfeld, S.E., Lienkaemper, J.J., McClellan, P., Williams, P.L. and Wong, I.G., editors (1992): Proceedings of the Second Conference on Earthquake Hazards in the Eastern San Francisco Bay Area; California Division of mines and Geology, Special Publication 113.

Kehew, A.E. (2000): Applied Chemical Hydrogeology; Prentice Hall.

Kelson, K.I., Lettis, W.R. and Lisowski, M. (1992): Distribution of Geologic Slip and Creep Along Faults in the San Francisco Bay Region; in Borchardt, G., Hirschfeld, S.E., Lienkaemper, J.J., McClellan, P., Williams, P.L. and Wong, I.G., editors (1992): Proceedings of the Second Conference on Earthquake Hazards in the Eastern San Francisco Bay Area; California Division of mines and Geology, Special Publication 113.

Kennedy, G.L., Lajoie, K.R., Blunt, D.J. and Mathieson, S.A. (1982): The Half Moon Bay terrace, San Mateo County, California, and the age of its Pleistocene invertebrate faunas; in Western Society of Malacologists, Annual Report, volume 14, p. 11-12.

Kennedy, D.G. and Caskey, S.J. (2002): Fault Propagation Folding Along the Serra Thrust Fault and Evidence for Late Pleistocene Onset of Transpression Along the San Andreas Fault, Northern San Francisco Peninsula, California.

Kirker, Chapman & Associates and Todd, D. K. (1972): Daly City groundwater Investigation, 159 p.

Kissick, C. (1997): Technical Memorandum 17, Volume 1; San Francisco Water department Groundwater Master Plan, Lake Merced Field Study; prepared for San Francisco Water Department; 16 p.

Kleinfelder, Inc. (1998): Limited Groundwater/Surface Water Assessment, Mussel Rock Landfill, Daly city, California; file number 44-0001-21.

Kleinfelder (2001a): Well Installation and monitoring Report, Mussel Rock Landfill, Daly City, California (file number 10-3012-65/003).

Kleinfelder, Inc. (2001b): Geologic and Slope Stability Evaluation Report, Mussel Rock Landfill, Daly City, California.

Kovach, R.L. and Beroza, G.C. (1991): Seismicity and faulting on the San Francisco Peninsula, in EOS, Transactions of the American Geophysical Union, volume 72, number 44, p. 447.

Krauskopf, K.B. (1979): Introduction to Geochemistry; McGraw-Hill Book Company, New York.

Lawson, A.C. (1893): The post-Pliocene diastrophism of the coast of southern California; University of California Publ., Bulletin Department of Geol. Sci., Volume 1, number 4, p. 115-160.

Lawson, A.C. (1895): Sketch of the geology of the San Francisco Peninsula; US Geological Survey Ann. Rept. 15, p. 405-476.

Lawson, A.C. (1908): The California Earthquake of April 18, 1906 – Report of the State Earthquake investigation Commission; in Carnegie Institution Washington Publications 87, volume 1, 451 p., atlas.

Lawson, A.C. (1914): Description of the San Francisco District; Tamalpais, San Francisco, Concord, San Mateo, and Hayward quadrangles: US Geological Survey Atlas, Folio 193.

Layne-Western Co. (1991): Pumping Test for San Bruno Water Department #14 City Park well on July 19, 1991.

Leighton, D.A., Fio, J.L. & Metzger, L.F. (1995): Database of Well and Areal Data, South San Francisco Bay and Peninsula Area, California.

Lisowski, M. and Savage, J.C. (1992): The Velocity Field in the San Francisco Bay Area and the inferred depth of creep on the Hayward Fault, in Borchardt, G., Hirschfeld, S.E., Lienkaemper, J.J., McClellan, P., Williams, P.L. and Wong, I.G., editors (1992): Proceedings of the Second Conference on Earthquake Hazards in the Eastern San Francisco Bay Area; California Division of mines and Geology, Special Publication 113.

Louderback, G.D. (1951): Geologic History of San Francisco Bay: California Division of Mines Bulletin 154, p. 75-94.

Luhdorff and Scalmanini Consulting Engineers (2002): Conceptualization of the Lake-Aquifer, System Westside Groundwater Basin, San Francisco and San Mateo Counties; a report prepared for San Francisco Public Utilities Commission.

Martin, B. (1916): The Pliocene of Middle and Northern California; University of California Publications, Bulletin of the Department of Geological Sciences, Volume 9, number 15, p. 215-259.

Meyer, C.E., Sarna-Wojcicki, A.M., Hillhouse, J.W., Woodward, M.J., Slate, J.L and Sorg, D.H. (1991): Fission-Track Age (400,000 yr) of the Rockland Tephra, Based on Inclusion of Zircon Grains Lacking Fossil Fission Tracks; in Quaternary Research, volume 35, p.367-382.

Michel, R.L. (1990): Tritium Deposition in the Continental United States, 1953-1983: United States Geological Survey Water-Resources Investigations Report 89-4072, 46 pp.

Miller, E.A. and Hall, E.B. (1966): A composition of soil shear strengths as determined with field and laboratory vane shear apparatus; American Society of Testing Materials, Special Technical Publication Number 399, p. 18-27.

Monet, J. (2000): Personal communication on water level readings at San Francisco State University.

Murchey, B. and Jones, D.L. (1984): Age and Significance of Chert in Franciscan Complex in the San Francisco Bay Region; in: Blake, M.C. (ed.): Franciscan Geology in Northern California; Pacific Section SEPM, Volume 43, pages 23-43.

Nzewe, O. (2000):

Olmsted, R. and Olmsted, N. (1979): Ocean Beach Study, a Survey of Historical Maps and Photographs; San Francisco Wastewater Program, 48 p.

Page, Ben M. (1966): Geology of the Coast Ranges of Califorina, in: Bailey, E.H. (1966): Geology of Northern California; California Division of Mines and Geology Bulletin 190; p.255-276.

Page, B.M. (1992): Tectonic Setting of the San Francisco Bay Region; in Borchardt, G., Hirschfeld, S.E., Lienkaemper, J.J., McClellan, P., Williams, P.L. and Wong, I.G., editors (1992): Proceedings of the Second Conference on Earthquake Hazards in the Eastern San Francisco Bay Area; California Division of mines and Geology, Special Publication 113.

Palache, C. (1894): The lherzolite serpentine and associated rocks of the Potrero, San Francisco; University of California Publication, Bulletin Department of Geological Sciences, Volume 1, number 5, p.161-179.

Pampeyan, E.H. (1994): Geologic Map of the Montara Mountain and San Mateo 7-1/2' Quadrangle, San Mateo County, CA, Scale: 1:24,000, USGS, Miscellaneous Investigation Series, Map I-2390.

Phillips, S.P., Hamlin, S.N. & Yates, E.B. (1993): Geohydrology, Water Quality, and Estimation of Groundwater Recharge in San Francisco, CA, 1987-92; Geological Survey; Water Resources Investigation Report 93-4019.

Potbury, S.S. (1932): A Pleistocene Flora from San Bruno, San Mateo County, Califorina; in studies of the Pleistocene paleobotany of California; Carnegie Institution of Washington, Contributions to the paleontology, Publication No.415 (1934), p. 25-44.

Potter, R.L. (1998): Mineralogical Controls on Groundwater Chemistry in the Merced Formation; A thesis submitted to the Department of Geosciences of San Francisco State University in Partial Fulfillment of the Requirements for the Degree of Bachelor of Science.

Prescott, W.H., Lisowski, M. and Savage (1981): Geodetic Measurements of Crustal Deformation on the San Andreas, Hayward and Calaveras faults near San Francisco, California; in Journal of Geophysical Research, volume 86, p. 10,853-10,869.

Reed, R.D. (1933): Geology of California; in Tulsa, Oklahoma, American Association of Petroleum Geologists, 355 p.

Robertson, W.D., Schiff, S.L. and Ptacek, C.J. (1998): Review of phosphate mobility and persistence in 10 septic system plumes; in: Groundwater 36, 1000-1010.

Ryer, T.A. (1977): Patterns of Cretaceous shallow-marine sedimentation, Colville and Rockport areas, Utah: Geological Society of America, volume 88, p.177-188.

San Francisco Department of Public Works (1974): Sewer System Evaluation for Infiltration Inflow, Phase 1, Richmond-Sunset District; San Francisco Department of Public Works, 45 p.

San Francisco Public Utilities Commission & San Francisco Recreation & Park Department (1997): Lake Merced Comprehensive Management Plan

San Mateo County Environmental Health Division (2000): Results of the April 2000 Westside Basin Twenty-Four Hour Well-Water Level Response Test; a report prepared by the Groundwater Protection Program for the Westside Basin Partners.

San Mateo County Environmental Health Division (2001a): Results of the 2000 Water Quality Analysis at selected wells in the Westside Groundwater Basin; prepared by the Groundwater Protection Program for the Westside Basin Partners.

San Mateo County Environmental Health Division (2001b): Results of the April 2001 Westside Basin Six-Hour Well-Water Level Response Test; prepared by San Mateo County Groundwater Protection Program for the Westside Basin Partners.

San Mateo County Environmental Health Division (2001c): Water Use in the Westside Groundwater Basin for the Year 2000; prepared by San Mateo County Groundwater Protection Program for the Westside Basin Partners.

San Mateo County Environmental Health Division (2002a): Results of the April 2001 Water Quality Analysis at selected wells in the Westside Groundwater Basin; prepared by San Mateo County Groundwater Protection Program for the Westside Basin Partners.

San Mateo County Environmental Health Division (2002b): Results of the October 2001 Westside Basin Six-Hour Well-Water Level Response Test; prepared by San Mateo County Groundwater Protection Program for the Westside Basin Partners.

San Mateo County Environmental Health Division (2002c): Results of the October 2001 Water Quality Analysis at selected wells in the Westside Groundwater Basin; prepared by San Mateo County Environmental Health Division for the Westside Basin Partners.

Sarna-Wojcicki, A.M. (1976): Correlation of late Cenozoic tuffs in the Central Coast Ranges of California by means of trace and minor-element chemistry; US Geological Survey Professional Paper 972, 30p.

Sarna-Wojcicki, A.M., Hall, N.T., Bowman, H.R. and Russell, P.C. (1977): Correlation of age of a widespread Pleistocene ash bed in northern California and western Nevada (abs.): Geological Society of America Abstracts with Programs, V.9, p.1155-1156.

Sarna-Wojcicki, A.M., Meyer, C.E., Bowman, H.R., Hall, N.T., Russell, P.C., Woodward, M.J., and Slate, J.L. (1985): Correlation of Rockland Ash bed, a 400,000 year-old stratigraphic marker in northern California and western Nevada, and implications for middle Pleistocene paleogeography of Central California; in Quaternary Research, volume 23, p. 236-257.

Sarna-Wojcicki, A.M. (1992): Long-Term Displacement Rates of the San Andreas Fault System in Northern California from the 6-Ma Roblar Tuff; in Borchardt, G., Hirschfeld, S.E., Lienkaemper, J.J., McClellan, P., Williams, P.L. and Wong, I.G., editors (1992): Proceedings of the Second Conference on Earthquake Hazards in the Eastern San Francisco Bay Area; California Division of mines and Geology, Special Publication 113.
Schlocker, J., Bonilla, M.G. and Radbruch, D.H. (1958): Geology of the San Francisco North Quadrangle, California; US Geological Survey Miscellaneous Geological Investigation Map I-272.

Schlocker, J. (1974): Geology of the San Francisco North Quadrangle, California: US Geological Survey Professional Paper 782, 109 p.

Seafriends (1997): Essential Elements in Living Organisms; http://www.seafriends.org.nz/oceano/abund.htm

Sedlock, R. (1995): Tectonic Framework, Origin and Evolution of the San Francisco Bay Region; in: Recent Geologic Studies in the San Francisco Bay Area, volume 76, edited by E.M. Sangines, D.W. Anderson, and A.V. Buising, pp. 1-18, Society of Economic Paleontologists and Mineralogists, Pacific Section; Los Angeles, California.

Seiders, V.M. (1988): Origin of Conglomerate Stratigraphy in the Franciscan Assemblage and Great Valley Sequence, Northern California; in: Geology, Volume 16, pages 783-787.

Shackleton, N.J. and Opdyke, N.D. (1973): Oxygen isotope and paleomagnetic stratigraphy of equatorial Pacific core V28-238; Oxygen isotope temperatures and ice volumes on a 10^5 and 10^6 years scale; in: Quaternary Research 3:39-53.

Shackleton, N.J. and Opdyke, N.D. (1976): Oxygen isotope and paleomagnetic stratigraphy of Pacific core V28-239 Late Pliocene to Late Pleistocene; in: Cline, R.M. and Hays, J.D. (editors) Investigation of Late Quaternary Paleoceanography and Paleoclimatology; Geological Society of America Memoir 145, pp. 449-464.

Smelser, M.G. (1987): Geology of the Mussel Rock Landslide, San Mateo County; in California Geology, March 1987; California Division of Mines and Geology, Volume 40, Number 3, pp. 59-66.

Smith, D.D. (1960): The Geomorphology of part of the San Francisco Peninsula, California; Stanford, California; Stanford University Ph.D. dissertation, 356 p.

Sowers, G.B. and Sowers, G. F. (1970): Introduction to Soil Mechanics and Foundations; McMillan Publishing Company, New York, 556 p.

Spellman, F.R. and Drinan, J. (2000): The drinking water handbook; Technomic Publishing Company.

Stetson Engineers Inc. (1992): Technical Memorandum; City of Burlingame, Washington Park Wells.

Steward, R.E and Steward, K.C. (1933): Notes on the foraminifera of the type Merced at Seven Mile Beach, San Mateo County, California; San Diego Society for Natural History Transactions, Volume 7, number 21, p.259-272.

Sullivan, R. (1975): Geological Hazards along the Coast South of San Francisco; California Geology CGEOA 28(2) p. 25-36.

Terzaghi, K. and Peck, R.B. (1968): Soil Mechanics in Engineering Practica; Second Edition, John Wiley and Sons Inc., New York.

Todd, D.K. (1971): On the Location of Well Number 14 for the City of San Bruno, California.

Trask, P.D. and Rolston, J.W. (1951): Engineering Geology of San Francisco Bay, California; Geological Society of America Bulletin, V. 62, p. 1079-1109.

Treasher, R.C. (1963): Geology of the Sedimentary Deposits in San Francisco Bay, California; California Division of Mines and Geology Special Report 82, p.11-24.

Trimble (1999): TSC Asset Surveyor, Operation Manual.

Underwood, M.B., Shelton, K.L., McLaughlin, R.J., McLaughland, M.M. and Solomon, R.M. (1999): Middle Miocene Paleotemperature Anomalies within the Franciscan Complex of northern California: Thermo-tectonic Responses near the Mendocino Triple Junction.

United States Coast Survey (1853): San Francisco Bay Between Point San Matheo [Coyote Point] and Guano Island; US Coast Survey, Register Number 433, Scale 1:10,000.

United States Coast Survey (1854): Untitled Map of Shoreline Area Between Point San Matheo [Coyote Point] and Millbrae; US Coast Survey, Register Number 460, scale 1:10,000.

United states Coast Survey (1857a): San Francisco Bay [between San Francisquito Creek and Guano Island]: US Coast Survey, Register Number 664, Scale 1:10,000.

United States Coast Survey (1857b): San Francisco Bay [Between Redwood City and Belmont]; US Coast Survey, Register Number 665, Scale 1:10,000.

United States Coast Survey (1867): Map Showing Approaches to San Francisco, California, for Use of Engineer Department, US Army; US Coast Survey, Register Number 1067, Scale 1:10,000.

United States Coast Survey (1868): Map Showing Approaches to San Francisco, California, for Use of Engineer Department, US Army, Millbrae and Vicinity; US Coast Survey, Register Number 1068, Scale 1:10,000.

United States Coast Survey (1869): San Francisco Peninsula; US Coast Survey, Register Number 3055, Scale 40,000.

United States Geological Survey: Digital Elevation Model (DEM); data set from the Bay Area Regional Database (BARD); http://bard.wr.usgs.gov/htmldir/dem_html/dem-sf.html.

United States Geological Survey (1994): Fact sheet on Digital Elevation Models (DEM); http://edcwww.cr.usgs.gov/glis/hyper/guide/usgs_dem.

United States Geological Survey (1994): USGS Water Resources Data – California, Water Year 1994; http://ca.water.usgs.gov/data/94/sw/sw11162720.uk2.html

United States Geological Survey (1996): California Hydrologic Data Report: Discontinued Water-Quality Stations; http://ca.water.usgs.gov/data/96/dis/wq.html

United States Geological Survey (1997): Investigation of the San Bruno Fault near the proposed extension of the Bay Area Rapid Transit Line from Colma to San Francisco International Airport, San Mateo County, California; Open-File Report 97-429.

Unites States Geological Survey (1999): USGS 1999 California Data Report: Discontinued Water-Quality Stations; http://ca.water.usgs.gov/data/99/disc_wq.html

United States Soil Conservation Service (1968): Soils of Santa Clara County, California; Washington D.C., US Government Printing Office, 227 p.

Versar-Sierra EnviroGroup (1995): Technical Report for Phase 1 of the Regional Water Quality control Board Clean-up Order 95-136, Task 1C: Bay Mud Study Evaluating the Risk to the Westside Basin, San Francisco International Airport, San Francisco, California, 20 p.

Versar-Sierra EnviroGroup (1996): Addendum to Technical Report for the Regional Water Quality Control Board Cleanup Order Task 1C: Evaluation of Risk to the Westside Basin, San Francisco International Airport, California.

Wagner, R.J. and Nelson, R.E (1961): Soil Survey of the San Mateo area, California: US Soil Conservation Service, Series 1954, no.13, 111p.

Wahrhaftig, C. (1984): A Streetcar to Subduction and other Plate Tectonic Trips by Public Transport in San Francisco.

Wahrhaftig, C., Stine, S.W. and Huber, N.K. (1993): Quaternary Geologic Map of the San Francisco Bay 4° x 6° Quadrangle, United States; Quaternary Geologic Atlas of the United States; United States Geologic Survey Miscellaneous Investigation Series Map I-1420 (NJ-10); prepared in cooperation with the Department of Geology and Geophysics, University of California, Berkeley.

Wakabayashi, J. (1992): Nappes, tectonics of oblique plate convergence, and metamorphic evolution related to 140 million years of continuous subduction, Franciscan Complex, California; in: Journal Geol., 100; 19-40.

Wakabayashi, J. and Hengesh, J.V. (1995): Distribution of Late Cenozoic Displacement on the San Andreas Fault System, Northern California; in: Recent Geologic Studies in the San Francisco Bay Area, volume 76, edited by E.M. Sangines, D.W. Anderson, and A.V. Buising, pp. 19-30, Society of Economic Paleontologists and Mineralogists, Pacific Section; Los Angeles, California.

Wakabayashi, J. (1999a): The Franciscan Complex, San Francisco Bay Area: A record of Subduction Complex Processes; in: Wagner, D.L. and Graham, S.A. (1999): Geologic

Field Trips in Northern Califorina; Centennial Meeting of the Cordilleran Section of the Geological Society of America; Geological Society of America Special Bulletin 119, p.1-21.

Wakabayashi, J. (1999b): Distribution of Displacement on and Evolution of a Young Transform System: The San Andreas Fault System, California; in Tectonics, Volume 18, Number 6, pp. 1245-1274.

Wakabayashi, J. and Unruh, J.R. (1999): Tectonic Wedging, Blueshist Metamorphism, and exposure of Blueshists: Are They Compatible?; in: Geology, Volume 23, Number 1, pages 85-88.

Weber, G.E. and Cotton, W.R. (1981): Geologic Investigation of Recurrence Intervals and Recurrence of Faulting along the San Gregorio Fault Zone, San Mateo County, California; US Geological Survey Open File Report 81-263, 133 p.

Wentworth, C.M., Ellen, S.D., Frizzell, V.A., Jr., and Schlocker, J. (1985): Map of hillside materials and description of their engineering character, San Mateo County, California: US Geological Survey Miscellaneous Investigations Map I-1257-D, scale 1:62,500.

Whitney, J.D. (1865): Geology of the Coast Ranges; Geological Survey of California; Geol., Volume 1, p.1-197.

Willis, B. (1938): San Andreas Rift, California; in Journal of Geology, volume 46, number 6, p. 793-827.

WITS (1999): Watershed Information Technical System. California Environmental Resources Evaluation System (CERES), California Resources Agency. http://ceres.ca.gov/watershed/

Woodward-Clyde Consultants (1980): Pump Test and Infiltration Test, Southwest Water Pollution Control Plant Project: San Francisco, California; Woodward-Clyde Consultants, Geotechnical Report to PBQ&D Inc., 8 p.

Woodward-Clyde Consultants (1985): Report on Final Inspection and Testing of Alvord Lake Irrigation Well, Golden Gate Park, San Francisco, California; Woodward-Clyde Consultants Letter Report to San Francisco Department of Public Works, October 25, 1985, 4 p.

Yates, E. B., Hamlin, S. N. and McCann, L. H. (1990): Geohydrology, Water Quality and Water Budgets of Golden Gate Park and Lake Merced Area in the Western Part of San Francisco, California; US Geological Survey Water-Resources Investigations Report 90-4080, 45 p.

Youd, T.L. and Perkins, J.B. (1987): Map Showing Liquefaction Susceptibility of San Mateo County, California; US Geological Survey Miscellaneous Investigation Series Map I-1257-G, Scale 1:62,500.

Appendix A: Water Quality Data:

WELL NAME	Chloride 05-00	Chloride 04-01	Chloride 10-01
Arboretum 5	31.80	29.00	NA
Elk Glenn 2	38.40	41.00	40.40
GG SL1	NA	31.00	NA
USGS South Mill D	89.10	91.00	NA
USGS S Windmill M	NA	43.00	NA
USGS South Mill S	42.90	94.00	NA
S Windmill	NA	41.00	41.80
NE Windmill	41.70	44.00	NA
West Sunset Playground	20.20	23.00	NA
Edgewood School	28.40	30.00	31.20
LMMW1S	112.00	130.00	NA
LMMW2S	60.60	76.00	NA
LMMW2D	39.10	66.00	NA
LMMW3S	92.90	100.00	NA
LMMW3D	73.20	91.00	NA
LMMW4S	NA	76.00	NA
LMMW5S	63.50	80.00	NA
LMMW6D	27.80	56.00	NA
Zoo4	43.40	NA	NA
Zoo5	NA	NA	53.00
Oceanside	64.30	82.00	NA
Fort Funston D	NA	20.00	NA
Fort Funston M	NA	12.00	NA
Fort Funston S	NA	33.00	NA
Olympic Country Club 8	NA	NA	97.60
San Francisco Golf Club 1	49.70	53.00	NA
Lake Merced Country Club	54.30	69.00	56.20
Westlake	108.00	110.00	120.00
DC 10	50.50	NA	NA
Jefferson	55.80	56.00	55.10
Vale	65.70	70.00	75.10
DC 04	65.20	NA	NA
A St	71.90	73.00	72.40
Home of Peace	77.60	NA	NA
Hills of Eternity	77.50	NA	NA
Cypress Lawn Cemetery So Well	69.10	80.00	NA
Holy Cross Cemetery 1	57.00	NA	NA
California Golf Club 5	103.00	NA	110.00
SS 1-14	120.00	120.00	130.00
SS 1-15	125.00	NA	NA
SS 1-18	91.00	NA	59.00
SS 1-19	121.00	120.00	130.00
SS 1-20	NA	160.00	160.00
SS 1-21	NA	160.00	NA
Vince's Shellfish	66.20	76.00	75.00
SB 15	98.00	NA	110.00
SB 16	107.00	110.00	110.00
SB 17	66.00	59.00	58.30
SB18	39.00	71.00	69.00

Green Hills Country Club	101.00	NA	NA
Pessagno	28.70	31.00	NA
812 Irwin Dr	161.00	NA	NA
510 Eucalyptus	9.14	NA	NA
Burlingame Country Club 3	67.50	NA	NA
25 New Place Rd	9.40	NA	NA
101 New Place Rd	44.00	NA	NA
1100 Jackling Dr	69.40	NA	NA
1700 Floribunda	4.91	NA	NA

Table A.1: *Wells sampled in 2000 and 2001 by the Westside Basin Partners, showing their chloride concentration in mg/L. None of the wells had a concentration above the secondary maximum contamination level of 250 mg/L set by the Environmental Protection Agency (1986). NA stands for not analyzed.*

WELL NAME	***Cl/Br 05-00***	***Cl/Br 04-01***	***Cl/Br 10-01***
Arboretum 5	NA	138.1	NA
Elk Glenn 2	NA	195.2	192.4
GG SL1	NA	73.8	NA
USGS South Mill D	114.2	233.3	NA
USGS S Windmill M	NA	204.8	NA
USGS South Mill S	127.3	303.2	NA
S Windmill	NA	273.3	261.3
Windmill NE	NA	258.8	NA
West Sunset Playground	61.2	143.8	NA
Edgewood School	NA	150.0	164.2
LMMW1S	172.6	282.6	NA
LMMW2S	173.6	422.2	NA
LMMW2D	139.6	347.4	NA
LMMW3S	126.6	212.8	NA
LMMW3D	120.0	245.9	NA
LMMW4S	NA	253.3	NA
LMMW5S	119.6	250.0	NA
LMMW6D	52.5	224.0	NA
Zoo4	111.3	NA	NA
Zoo5	NA	NA	265.0
Oceanside	139.8	134.4	NA
Fort Funston D	ND	24.4	NA
Fort Funston M	ND	25.5	NA
Fort Funston S	ND	34.7	NA
San Francisco Golf Club MW	138.1	278.9	NA
Olympic Country Club 9	NA	NA	238.0
Lake Merced Country Club	100.6	202.9	234.2
Westlake Well	NA	275.0	292.7
Jefferson	NA	294.7	306.1
Vale	NA	291.7	312.9
A St	NA	280.8	289.6
Cypress Lawn Cemetery So Well	NA	275.9	NA
California Golf Club 5	166.1	NA	314.3
SS 1-14	NA	222.2	194.0
SS 1-18	NA	ND	122.9

SS 1-19	NA	244.9	265.3
SS 1-20	NA	320.0	313.7
SS 1-21	NA	320.0	NA
Vince's Shellfish	132.4	361.9	357.1
SB 15	NA	NA	343.8
SB 16	NA	333.3	354.8
SB 17	NA	347.1	342.9
SB18	NA	355.0	300.0
852 Hawthorne	NA	182.4	NA
812 Irwin Dr	NA	NA	NA
510 Eucalyptus	NA	NA	NA
Burlingame Country Club 3	135.0	NA	NA

Table A.2: *Chloride-to-bromide ratios for wells sampled by Westside Basin Partners in 2000 and 2001 (San Mateo County Environmental Health Division, 2001a, 2002a, 2002c). The ratio of many wells is close to that of seawater set at 300.*

WELL NAME	Cl/B 05-00	Cl/B 04/01	Cl/B 10/01
Arboretum #5	NA	36.25	NA
Elk Glenn 2	NA	51.25	1154.29
SL1	NA	41.33	NA
USDS S Windmill D	17.82	478.95	NA
USGS S Windmill M	NA	65.15	NA
USGS S Windmill S	NA	3760.00	NA
NE Windmill	NA	51.76	NA
S Windmill	NA	48.81	908.70
West Sunset Playground	NA	766.67	NA
Edgewood School	NA	75.00	945.45
Zoo 5	NA	NA	1325.00
Oceanside	NA	15.77	NA
LMMW1S	NA	4482.76	NA
LMMW2D	NA	2275.86	NA
LMMW2S	NA	2054.05	NA
LMMW3D	NA	1716.98	NA
LMMW3S	NA	5555.56	NA
LMMW4S	NA	513.51	NA
LMMW5S	NA	2962.96	NA
LMMW6D	NA	2074.07	NA
Fort Funston D	NA	25.97	NA
Fort Funston M	NA	12.77	NA
Fort Funston S	NA	76.74	NA
Olympic Country Club 8	NA	NA	2568.42
San Francisco Golf Club MW	NA	72.60	NA
Lake Merced Country Club	NA	3833.33	2957.89
Westlake Well	NA	2500.00	3000.00
Jefferson	NA	2000.00	2504.55
Vale Well	NA	2800.00	3413.64
A Street Well	NA	3318.18	3810.53
Cypress Lawn Cemetery So Well	NA	3200.00	NA
SS 1-14	NA	6315.79	2241.38
SS 1-18	NA	NA	1229.17
SS 1-19	NA	2666.67	3421.05

SS 1-20	NA	5333.33	2461.54
SS 1-21	NA	2807.02	NA
California Golf Club 5	NA	NA	2500.00
Vince's Shellfish Co	NA	2111.11	2272.73
SB 15	NA	NA	2500.00
SB 16	NA	1641.79	2820.51
SB 17	NA	1340.91	1325.00
SB 18	NA	1577.78	1916.67
852 Hawthorne	NA	837.84	NA
Burlingame Country Club 3	421.88	NA	NA

Table A.3: *Chloride-to-boron ratios for wells sampled by Westside Basin Partners in May of 2000 and April and October of 2001. The ratio of many wells is close to that of seawater set at 4220.*

WELL NAME	MBAS 05-00
Arboretum #5	ND
Elk Glenn 2	ND
NE Windmill	ND
Edgewood School	ND
Home of Peace	ND
Hills of Eternity	ND
Cypress Lawn Cemetery So Well	ND
Holy Cross Cemetery 1	ND
Green Hills Country Club	ND
852 Hawthorne	ND
812 Irwin Dr	ND
510 Eucalyptus	ND
25 New Place Rd	ND
101 New Place Rd	ND
1100 Jackling Dr	ND
1700 Floribunda	ND

Table A.4: *Methylene active blue substances (MBAS) values for wells sampled in May 2000. MBAS was not detected at any of the analyzed wells indicating that at these location sewage has not affected groundwater or that detergents have already been chemically decomposed and removed from groundwater.*

WELL NAME	K 05-00	K 04-01	K 10-01
Arboretum 5	1.39	0.26	1.08
Elk Glenn 2	ND	2.30	NA
USGS South Mill D	6.04	9.40	NA
USGS South Mill M	NA	6.10	NA
USGS South Mill S	4	0.34	NA
GG SL1	NA	0.62	NA
Windmill NE	ND	1.50	NA
S Windmill	NA	1.50	1.60
West Sunset Playground	1.90	0.35	NA
Edgewood School	4.97	5.40	1.44

LMMW1S	3.59	1.40	NA
LMMW2S	13.60	1.10	NA
LMMW2D	10.10	14.00	NA
LMMW3S	1.87	0.84	NA
LMMW3D	8.10	1.00	NA
LMMW4S		12.00	NA
LMMW5S	9.75	4.60	NA
LMMW6D	13.30	5.30	NA
Oceanside	NA	5.10	NA
Zoo4	2.33	NA	NA
ZOO 5	NA	NA	1.97
Fort Funston M	NA	3.30	NA
Fort Funston S	NA	39.00	NA
Fort Funston D	NA	0.70	NA
San Francisco Golf Club 1	ND	0.70	NA
OLYMPIC C CLUB 8	NA	NA	1.91
Lake Merced Country Club	3.16	0.84	1.71
Westlake 1	2.83	1.80	2.81
DC 10	1.48		
Jefferson	1.71	1.00	1.84
Vale	2.68	0.80	2.01
DC 04	1.83	NA	NA
A St	2.19	0.78	1.85
Home of Peace	1.15	NA	NA
Hills of Eternity	1.38	NA	NA
Cypress Lawn Cemetery 2	1.57	0.54	NA
Holy Cross Cemetery 1	1.11	NA	NA
California Golf Club 5	3.67	NA	2.20
SS 1-14	3.0	21.00	2.51
SS 1-15	3.2	NA	NA
SS 1-18	3.0	NA	2.48
SS 1-19	2.8	6.10	2.22
SS 1-20	NA	1.40	4.43
SS 1-21	NA	4.20	NA
Vince's Shellfish	4.88	4.60	2.21
SB 15	3.4	NA	3.05
SB 16	4.3	4.80	3.32
SB 17	4.0	2.50	3.35
SB18	4.1	2.80	3.37
Green Hills Country Club	4.82	NA	NA
852 Hawthorne	ND	2.40	NA
812 Irwin Dr	ND	NA	NA
510 Eucalyptus	NA	NA	NA
Burlingame Country Club 3	2.67	NA	NA
25 New Place Rd	NA	NA	NA
101 New Place Rd	ND	NA	NA
1100 Jackling Dr	ND	NA	NA
1700 Floribunda	NA	NA	NA
Oceanside	67.80	NA	NA

Table A.5: *Potassium concentration in well sampled by the Westside Bain Partners in 2000 and 2001 (San Mateo County Environmental Health Division, 2001a, 2002a, 2002c).*

WELL NAME	pH 05-00	HCO3 05-00	CO3 05-00	PO4 05-00	pH 04-01	HCO3 04-01	CO3 04-01	PO4 04-01
Arboretum 5	7.08	171	ND	ND	6.9	170	<1	0.06
Elk Glenn 2	7.65	138	ND	ND	7.6	140	<1	0.08
GG SL1	NA	NA	NA	NA	7.4	130	<1	0.09
USGS South Mill D	7.84	439	ND	ND	7.9	480	16	0.10
USGS S Windmill M	NA	NA	NA	NA	7.5	180	<1	0.11
USGS South Mill S	7.72	173	ND	ND	6.8	240	<1	0.03
S Windmill	NA	NA	NA	NA	7.5	140	<1	0.09
NE Windmill	7.30	175	ND	ND	7.3	180	<1	0.11
West Sunset Playground	9.40	28.7	22.1	ND	**9.3**	44	16	<0.03
Edgewood School	7.37	108	ND	ND	7.1	100	<1	<0.03
LMMW1S	6.79	177	ND	ND	6.4	170	<1	0.12
LMMW2S	6.76	61.8	ND	ND	6.6	76	<1	0.12
LMMW2D	6.91	76.2	ND	ND	6.9	84	<1	0.18
LMMW3S	7.36	204	ND	ND	7.6	220	<1	<0.03
LMMW3D	11.40	ND	16.5	ND	**11.8**	ND	12	<0.03
LMMW4S	NA	NA	NA	NA	7.4	140	<1	0.04
LMMW5S	7.32	196	ND	ND	6.8	220	<1	<0.03
LMMW6D	11.30	0	20.6	ND	**11.4**	ND	24	<0.03
Zoo4	7.71	157	ND	ND	NA	NA	NA	NA
Zoo5	NA	NA	NA	NA	NA	NA	NA	NA
Oceanside	9.35	139	ND	ND	**9.3**	72	48	<0.03
Fort Funston D	NA	NA	NA	NA	7.4	240	<1	0.03
Fort Funston M	NA	NA	NA	NA	7.0	26	<1	<0.03
Fort Funston S	NA	NA	NA	NA	7.7	220	<1	<0.03
Olympic Country Club 8	NA	NA	NA	NA	NA	NA	NA	NA
San Francisco Golf Club 1	8.05	88.6	ND	ND	8.1	96	<1	0.09
Lake Merced Country Club	7.91	150	ND	ND	7.8	170	<1	0.04
Westlake Well	7.66	190	ND	NA	7.8	180	<1	0.06
DC 10	8.12	113	ND	NA	NA	NA	NA	NA
Jefferson	8.10	114	ND	NA	8.1	110	<1	0.07
Vale	8.14	122	ND	NA	8.0	120	<1	0.05
DC 04	8.12	126	ND	NA	NA	NA	NA	NA
A St	8.10	113	ND	NA	8.2	110	<1	0.06
Home of Peace	7.67	195	ND	ND	NA	NA	NA	NA
Hills of Eternity	7.75	161	ND	ND	NA	NA	NA	NA
Cypress Lawn Cemetery So Well	8.23	155	ND	ND	7.4	170	<1	0.04
Holy Cross Cemetery 1	8.12	137	ND	ND	NA	N	NA	NA
California Golf Club 5	7.81	190	ND	ND	7.6	NA	NA	0.04
SS 1-14	7.55	360	ND	NA	NA	250	<1	NA
SS 1-15	7.43	310	ND	0.17	NA	NA	NA	NA
SS 1-18	7.80	250	1.1	0.05	NA	NA	NA	NA
SS 1-19	7.81	257	1.1	0.15	7.9	220	<1	0.04
SS 1-20	NA	A	NA	NA	7.6	220	<1	0.30
SS 1-21	NA	NA	NA	NA	7.4	230	<1	0.12
Vince's Shellfish	7.44	146	ND	ND	7.3	140	<1	0.07
SB 15	6.90	168	ND	NA	NA	NA	NA	NA
SB 16	7.50	170	ND	NA	7.2	190	<1	0.08
SB 17	7.60	152	ND	NA	7.8	160	<1	0.15
SB18	7.70	130	ND	NA	7.6	130	<1	0.09

Green Hills Country Club	7.16	175	ND	ND	NA	NA	NA	NA
Pessagno	6.74	133	ND	NA	6.5	160	<1	0.27
812 Irwin Dr	8.46	NA	NA	NA	NA	NA	NA	NA
510 Eucalyptus	8.93	49.4	ND	NA	NA	NA	NA	NA
Burlingame Country Club 3	7.94	173	20.6	ND	NA	NA	NA	NA
25 New Place Rd	8.92	49.4	ND	NA	NA	NA	NA	NA
101 New Place Rd	6.95	173	ND	NA	NA	NA	NA	NA
1100 Jackling Dr	6.79	136	ND	NA	NA	NA	NA	NA
1700 Floribunda	9.10	31	ND	NA	NA	NA	NA	NA

Table A.6: *pH, bicarbonate alkalinity, carbonate alkalinity and phosphate concentrations in wells sampled by the Westside Basin Partners in 2000 and 2001 (San Mateo County Environmental Health Division, 2001a, 2002a). Although phosphate values are pH dependent, and, therefore, higher at higher pH values, phosphate concentration is overall low. No specific correlation between carbonate and bicarbonate alkalinity and phosphate can be observed. ND stands for not detected and NA for not analyzed.*

WELL NAME	**Cl:SO4 05-00**	**Cl:SO4 04-01**	**Cl:SO4 10-01**
Arboretum 5	0.86	0.88	NA
Elk Glenn	0.79	0.79	0.80
SL1	NA	0.69	NA
USGS South Mill D	2.00	3.25	NA
USGS South Mill M	NA	0.98	NA
USGS South Mill S	1.02	1.74	NA
Windmill NE	1.00	1.13	NA
Windmill S	NA	1.52	1.31
West Sunset Playground	2.45	1.53	NA
Edgewood School	0.88	0.86	0.85
LMMW1S	4.01	4.64	NA
LMMW2S	5.32	5.43	NA
LMMW2D	6.09	8.25	NA
LMMW3S	3.67	3.57	NA
LMMW3D	7.39	8.27	NA
LMMW4S	NA	2.24	NA
LMMW5S	1.52	1.82	NA
LMMW6D	4.55	3.29	NA
Oceanside	81.39	>273.33	NA
Zoo4	1.15	NA	NA
Zoo5	NA	NA	2.39
Fort Funston D	NA	1.43	NA
Fort Funston M	NA	3.00	NA
Fort Funston S	NA	0.58	NA
San Francisco Golf Club MW	5.74	5.30	NA
Olympic Country Club 8	NA	NA	2.99
Lake Merced Country Club	1.53	1.50	1.68
Westlake 1	1.27	1.20	1.24
DC 10	1.82	NA	NA
Jefferson	5.12	5.09	4.88
Vale	2.55	3.04	3.03
DC 04	2.02	NA	NA
A St	3.49	4.29	4.26

Home of Peace	1.57	NA	NA
Hills of Eternity	1.83	NA	NA
Cypress Lawn Cemetery 2	2.33	2.76	NA
Holy Cross Cemetery 1	2.84	NA	NA
California Golf Club 5	1.62	NA	1.75
SS 1-14	1.22	1.45	1.00
SS 1-15	1.79	NA	NA
SS 1-18	1.60	NA	0.70
SS 1-19	2.24	1.85	2.00
SS 1-20	NA	0.89	0.80
SS 1-21	NA	0.80	NA
Vince's Shellfish	3.01	3.17	3.19
SB 15	1.31	NA	1.42
SB 16	1.45	1.39	1.39
SB 17	2.28	2.19	2.14
SB18	1.95	3.38	3.30
Green Hills Country Club	1.02	NA	NA
852 Hawthorne	0.87	1.03	NA
812 Irwin Dr	4.76	NA	NA
510 Eucalyptus	0.63	NA	NA
Burlingame Country Club 3	1.07	NA	NA
25 New Place Rd	0.53	NA	NA
101 New Place Rd	1.47	NA	NA
1100 Jackling Dr	1.91	NA	NA
1700 Floribunda	0.56	NA	NA

Table A.7: *Chloride-to-sulfate ratios for water sampled collected by the Westside Basin partners in May 2000 and April and October 2001. In comparison, chloride-to-sulfate ratio of seawater is about 7.00. Of all the collected samples the ratios of LMMW2D and LMMW3D are close to that of seawater (marked in red). The extremely high chloride-to-sulfate ratio of the Oceanside well is due to an unusually low sulfate concentration in the well water. NA stands for not analyzed.*

WELL NAME	NO3 05-00	NO3 04-01	NO3 10-01
Arboretum 5	**49.00**	**77.0**	NA
Elk Glenn 2	**49.20**	**55.0**	**48.90**
GG SL1	NA	32.0	NA
USGS South Mill D	0.93	<0.2	NA
USGS South Mill M	NA	29.0	NA
USGS South Mill S	26.60	35.0	NA
S Windmill	NA	38.0	37.90
NE Windmill	27.70	28.0	NA
West Sunset Playground	ND	<0.2	NA
Edgewood School	33.80	44.0	**45.60**
LMMW1S	35.60	37.0	NA
LMMW2S	0.91	2.2	NA
LMMW2D	3.04	0.3	NA
LMMW3S	ND	0.8	NA
LMMW3D	0.64	<0.2	NA

LMMW4S	NA	**95.0**	NA
LMMW5S	27.50	22.0	NA
LMMW6D	1.62	<0.2	NA
Zoo4	33.10	NA	NA
Zoo5	NA	NA	22.70
Oceanside	0.63	<0.2	NA
Fort Funston D	NA	0.4	NA
Fort Funston M	NA	0.7	NA
Fort Funston S	NA	<0.2	NA
Olympic Country Club 8	NA	NA	1.70
San Francisco Golf Club 1	3.43	3.9	NA
Lake Merced Country Club	33.10	40.0	36.40
Westlake Well	31.60	28.0	27.30
DC 10	40.60	NA	NA
Jefferson	11.60	11.0	10.60
Vale	33.40	33.0	35.90
DC 04	42.20	NA	NA
A St	**53.50**	**57.0**	**63.40**
Home of Peace	**85.40**	NA	NA
Hills of Eternity	**98.60**	NA	NA
Cypress Lawn Cemetery So Well	**46.90**	**58.0**	NA
Holy Cross Cemetery 1	41.30	NA	NA
California Golf Club 5	6.34	NA	6.40
SS 1-14	53.00	36.0	60.00
SS 1-15	28.00	NA	NA
SS 1-18	**69.00**	NA	**61.60**
SS 1-19	31.00	33.0	36.90
SS 1-20	NA	4.1	7.00
SS 1-21	NA	<0.2	NA
Vince's Shellfish	1.38	1.1	1.00
SB 15	8.50	NA	3.30
SB 16	ND	0.3	0.30
SB 17	3.50	3.9	3.80
SB18	5.80	5.9	6.00
Green Hills Country Club	16.00	NA	NA
852 Hawthorne	5.85	3.2	NA
812 Irwin Dr	8.63	NA	NA
510 Eucalyptus	3.89	NA	NA
Burlingame Country Club 3	1.29	NA	NA
25 New Place Rd	3.96	NA	NA
101 New Place Rd	2.90	NA	NA
1100 Jackling Dr	33.40	NA	NA
1700 Floribunda	0.67	NA	NA

Table A.8: *Nitrate (as nitrate) concentration in well water samples collected by the Westside Basin Partners (San Mateo County Environmental Health Division 2001a, 2002a, 2002c) in May of 2000 and April and October of 2001.Values marked in red are* *those that exceed primary maximum concentration level of 45 mg/L set by the Environmental Protection Agency (1986).*

WELL NAME	Ca/Mg 05-00	Ca/Mg 04-01	Ca/Mg 10-01
Arboretum 5	0.76	0.97	0.94
Elk Glenn 2	0.93	6.84	NA
GG SL1	NA	0.97	NA
USGS South Mill D	0.98	1.53	NA
USGS S Windmill M	NA	1.10	NA
USGS South Mill S	0.86	1.00	NA
S Windmill	NA	0.81	0.90
NE Windmill	0.80	1.00	NA
West Sunset Playground	1.01	1.08	NA
Edgewood School	17.83	1.64	0.98
LMMW1S	0.67	2.50	NA
LMMW2S	2.99	0.66	NA
LMMW2D	3.38	3.19	NA
LMMW3S	0.86	1.00	NA
LMMW3D	NA	0.87	NA
LMMW4S	NA	2.00	NA
LMMW5S	1.69	0.93	NA
LMMW6D	101.67	261.11	NA
Zoo4	0.89	NA	NA
Zoo5	NA	NA	0.88
Oceanside	1.36	0.24	NA
Fort Funston D	NA	6.11	NA
Fort Funston M	NA	4.72	NA
Fort Funston S	NA	2.67	NA
Olympic Country Club 8	NA	NA	0.82
San Francisco Golf Club 1	0.95	0.84	NA
Lake Merced Country Club	1.06	1.03	1.01
Westlake Well	1.07	1.06	1.00
DC 10	0.81	NA	NA
Jefferson	0.98	0.95	0.97
Vale	0.91	1.08	1.06
DC 04	0.83	NA	NA
A St	0.90	1.04	1.04
Home of Peace	1.12	NA	NA
Hills of Eternity	1.10	NA	NA
Cypress Lawn Cemetery So Well	1.00	1.11	NA
Holy Cross Cemetery 1	0.97	NA	NA
California Golf Club 5	1.01	NA	0.95
SS 1-14	0.17	25.00	0.84
SS 1-15	1.04	NA	NA
SS 1-18	1.28	NA	0.91
SS 1-19	0.98	1.05	0.80
SS 1-20	NA	0.86	1.91
SS 1-21	NA	2.68	NA
Vince's Shellfish	2.18	2.00	2.28
SB 15	4.15	NA	1.25
SB 16	1.60	2.04	1.43
SB 17	1.62	1.50	1.62

SB18	1.78	1.70	1.32
Green Hills Country Club	1.56	NA	NA
852 Hawthorne	1.56	1.33	NA
812 Irwin Dr	0.83	NA	NA
510 Eucalyptus	3.73	NA	NA
Burlingame Country Club 3	3.29	NA	NA
25 New Place Rd	3.67	NA	NA
101 New Place Rd	1.19	NA	NA
1100 Jackling Dr	1.96	NA	NA
1700 Floribunda	3.92	NA	NA

Table A.9: *Calcium-to-magnesium ratios for samples collected by the Westside Basin Partners in 2000 and 2001 (San Mateo County Environmental Health Division, 2000a, 2001a, 2001c). Except for one sample collected at the Oceanside well none of the samples has ratios similar to that of seawater.*

Appendix B

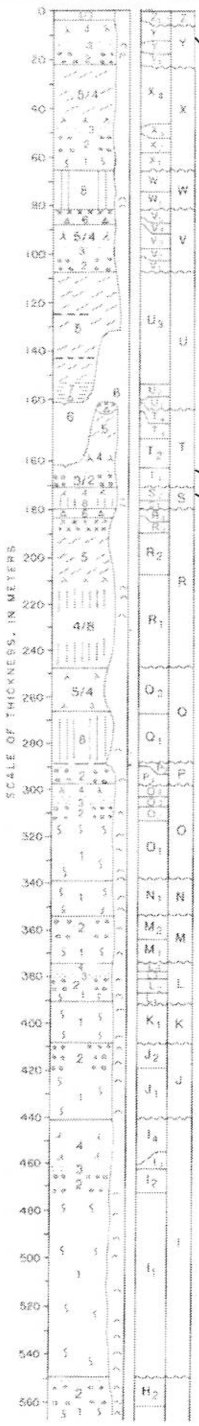
USCS Group Symbol	USCS Typical Names	Clifton and Hunter's Textural Description	Inferred Origin	Fig.3 in Clifton and Hunter (1989)
GW	Well graded gravels, gravel-sand mixtures, little or no fines	pebbly sand and gravel	Alluvial	6
GP	Poorly graded gravels, gravel-sand mixtures, little or no fines	very fine sand, scattered small pebbles near top	Inner shelf	1
GM	Silty gravels, poorly graded gravel-sand-silt mixtures	Mud, sand and gravel, upward-fining cycles	Embayment	8
GC	Clayey gravel, poorly graded gravel-sand-clay mixture	Mud, sand and gravel, upward-fining cycles	Embayment	8
SW	Well graded sands, gravelly sands, little or no fines	pebbly sand and gravel	Alluvial	6
		fine sand	Backshore	4
		fine sand	Eolian dune	5
SP	Poorly graded sands, gravelly sands, little or no fines	fine to coarse sand and gravel	Nearshore	2
		fine to coarse sand and gravel, upward fining	Foreshore	3
SM	Silty sands, poorly graded sand-silt mixtures	sandy silt	Outer shelf	1
		sandy silt	Mid Shelf	1
SC	Clayey sands, poorly graded sand-clay mixtures	sandy silt	Outer shelf	1
		sandy silt	Mid Shelf	1
ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity	sandy silt	Outer shelf	1
		sandy silt	Mid Shelf	1
CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	very fine sand, scattered small pebbles near top	Inner shelf	1

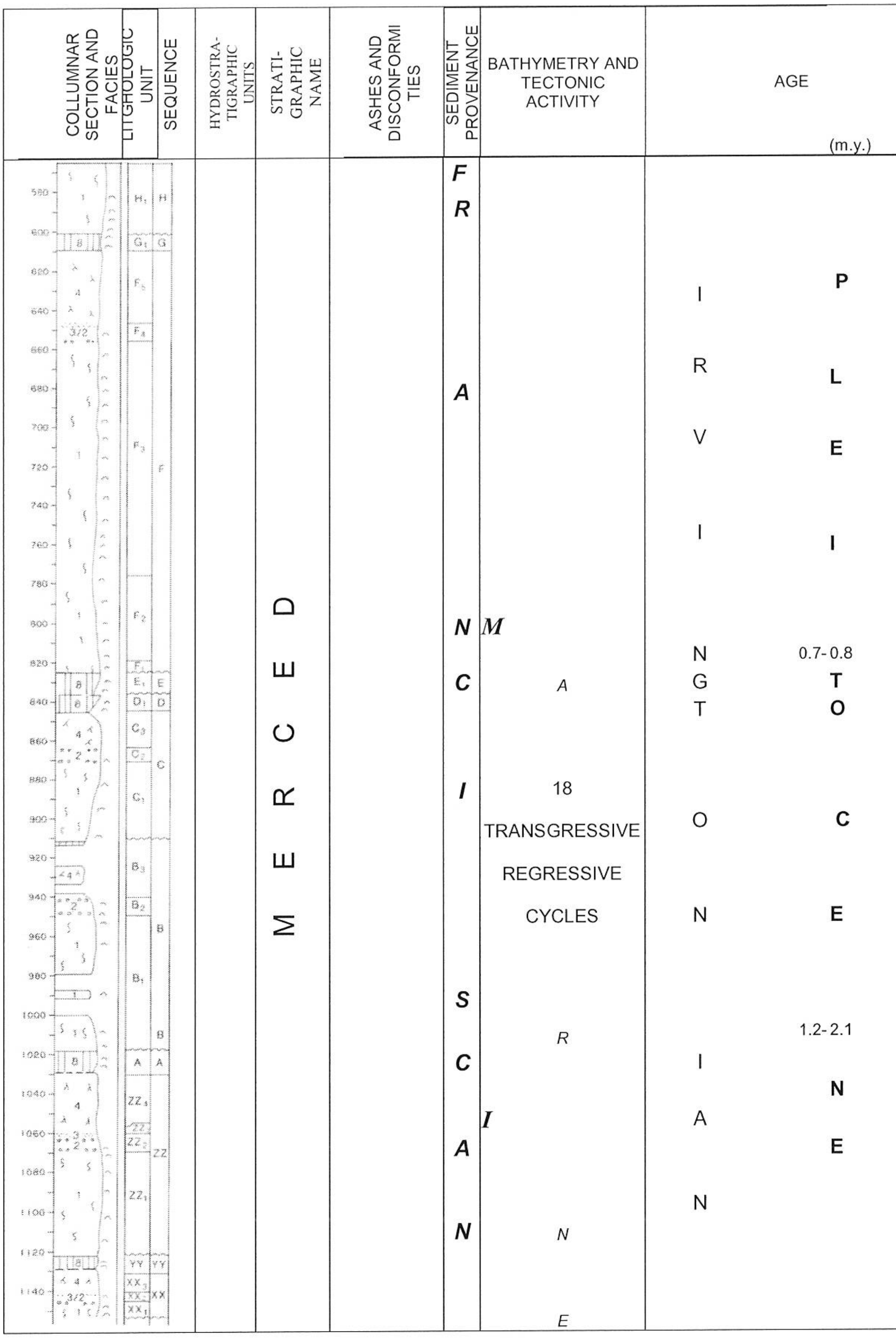
OL	Organic silts and organic silt-clays of low plasticity	-	-	
MH	Inorganic silts, micaceous or diatomaceous fine, sandy or silty soils, elastic silts	-	-	
CH	Inorganic clays of high plasticity, fat clays	mud	Embayment	8
OH	Organic clays of medium to high plasticity	-	-	
Pt	Peat and other highly organic soils	mud, peat, lignite	Pond/swamp/marsh	7

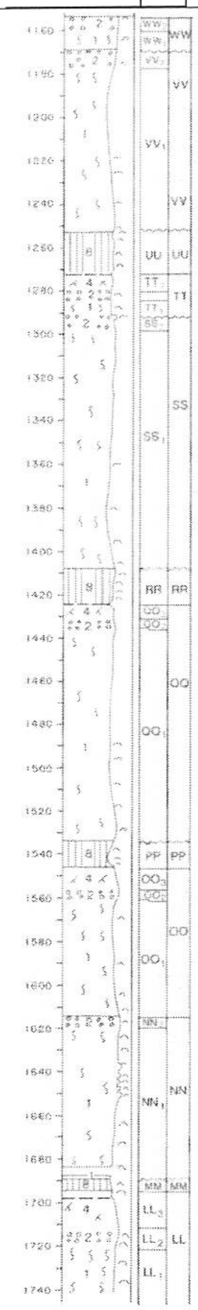
Table 4.1: *Comparison between the Unified Soil Classification System (USCS) and the sediments description and inferred sediment origin according to Clifton and Hunter (1989).*

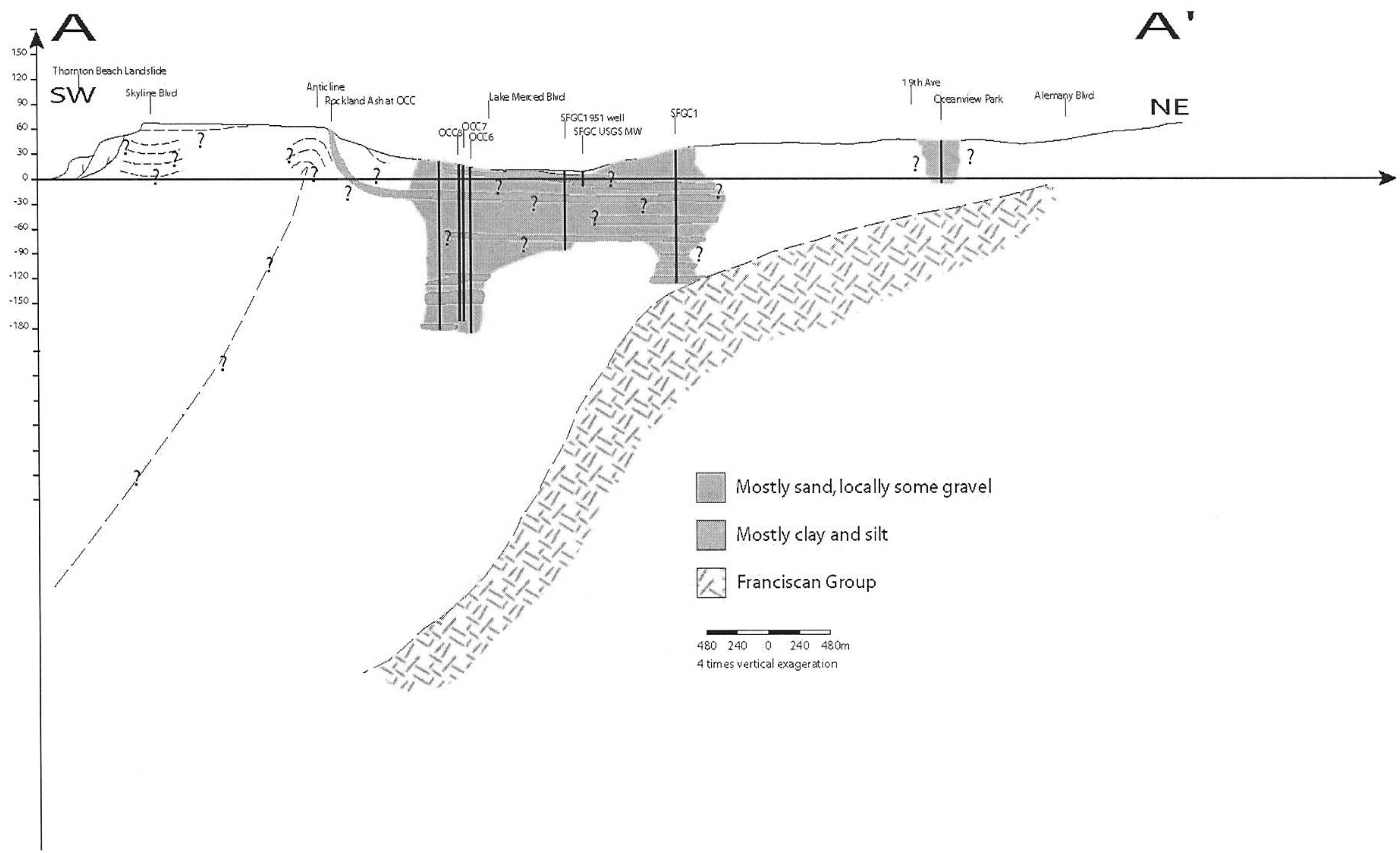
Appendix C

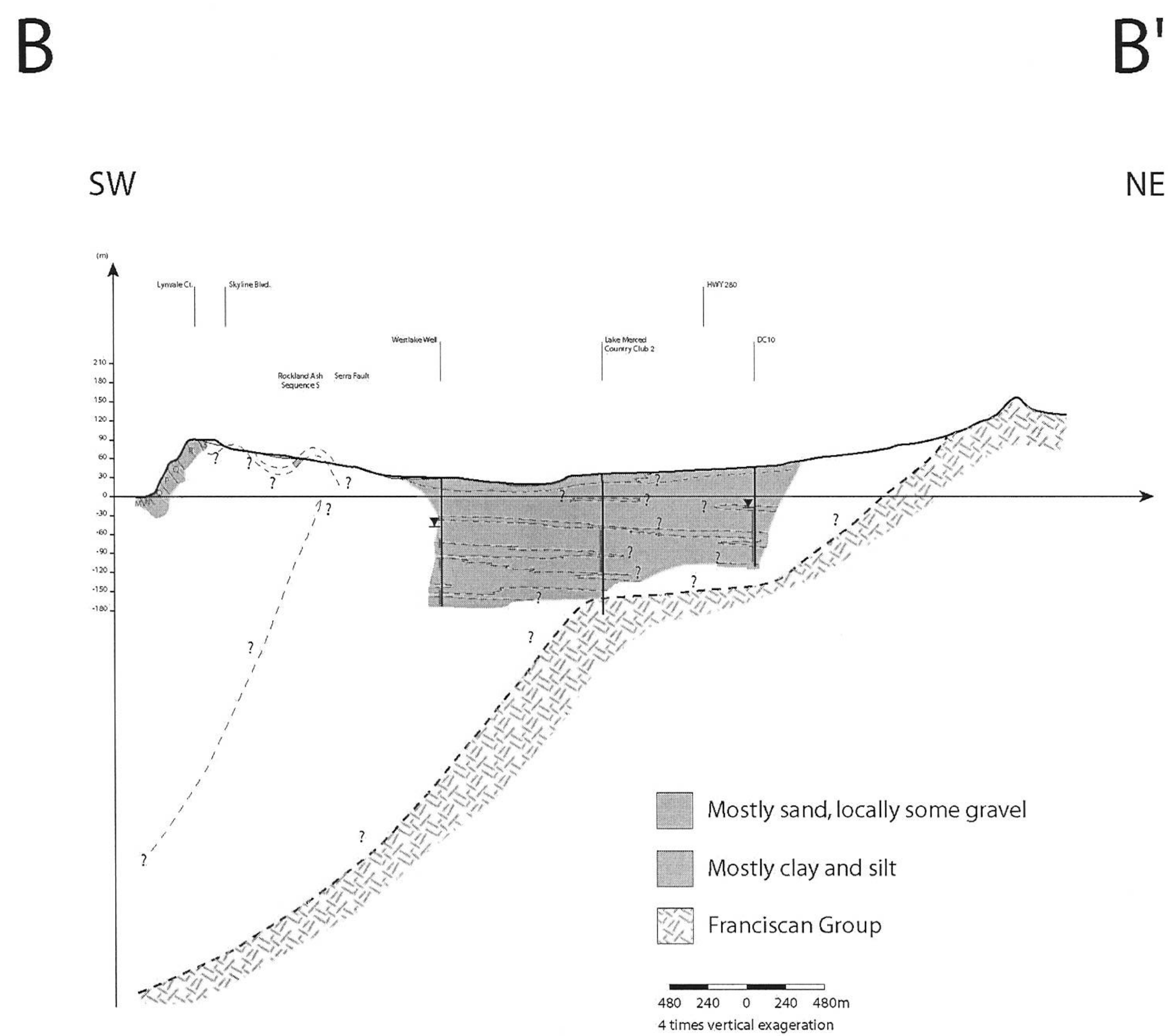
Stratigraphic characteristics of the Westside Basin. Compiled with data from Hall (1966), Addicott (1969), Clifton and Stage (1986), Clifton and Hunter (1987, 1991, 1999), Clifton (1989) and Ingram and Ingle (1998). Stratigraphic column adapted from Clifton and Hunter (1991). The various symbols shown in the columns represent different facies of the Merced and Colma formations. Numbers are assigned to these symbols: 1, shelf (including outer-shelf, mid-shelf and inner-shelf facies); 2, nearshore (may include foreshore facies in some sequences); 3, foreshore; 4, backshore; 5 eolian dune; 6, alluvium; 7, freshwater/swamp/marsh; 8, embayment.

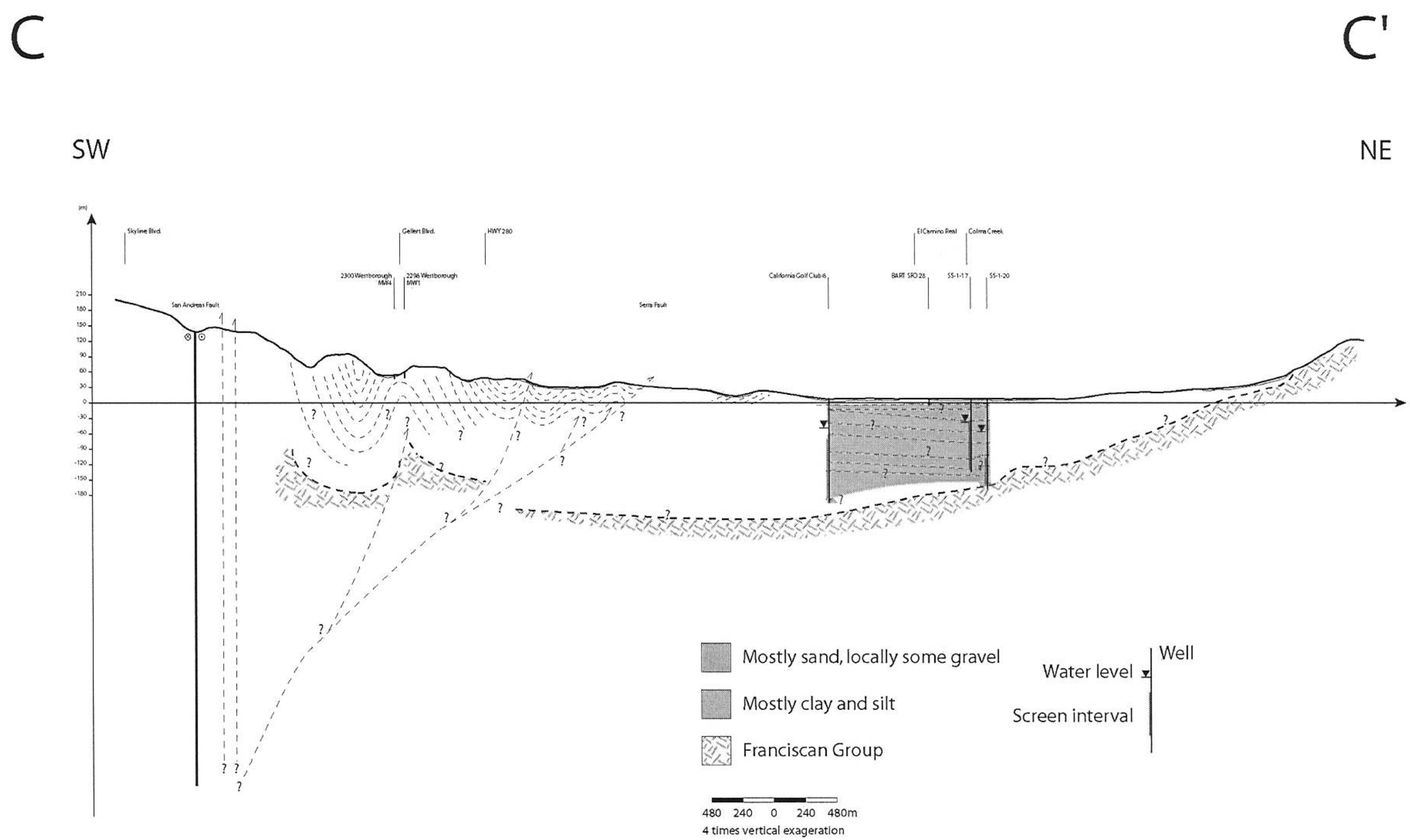
COLLUMNAR SECTION AND FACIES / LITGHOLOGIC UNIT / SEQUENCE	HYDROSTRA-TIGRAPHIC UNITS	STRATI-GRAPHIC NAME	ASHES AND DISCONFORMITIES	SEDIMENT PROVENANCE	BATHYMETRY AND TECTONIC ACTIVITY	AGE (m.y.)		
	HS1	BAY MUDS					HOLOCENE	
	HS2	ALLUVIUM						
	HS3	COLMA	OLEMA ASH	S I E R R A N	1 TRANSGRESSIVE /REGRESSIVE CYCLE	SANGAMON	oxygen isotope stage 5	0.055 0.127
	HS4 HS5 HS6a HS6b HS7	MERCED	DISCON-FORMITY ROCKLAND ASH		5 TRANSGRESSIVE REGRESSIVE CYCLES	I R V I N G T O N I A N	P L E I S T O C E N E	0.2 0.4 (0.61)
	HS8 HS9 HS10 HS11				18 TRANSGRESSIVE CYCLES (T E R R E S T R I A L)			0.6 0.59- 0.65
				F R A N C I S C A N	MARINE			0.64- 0.7

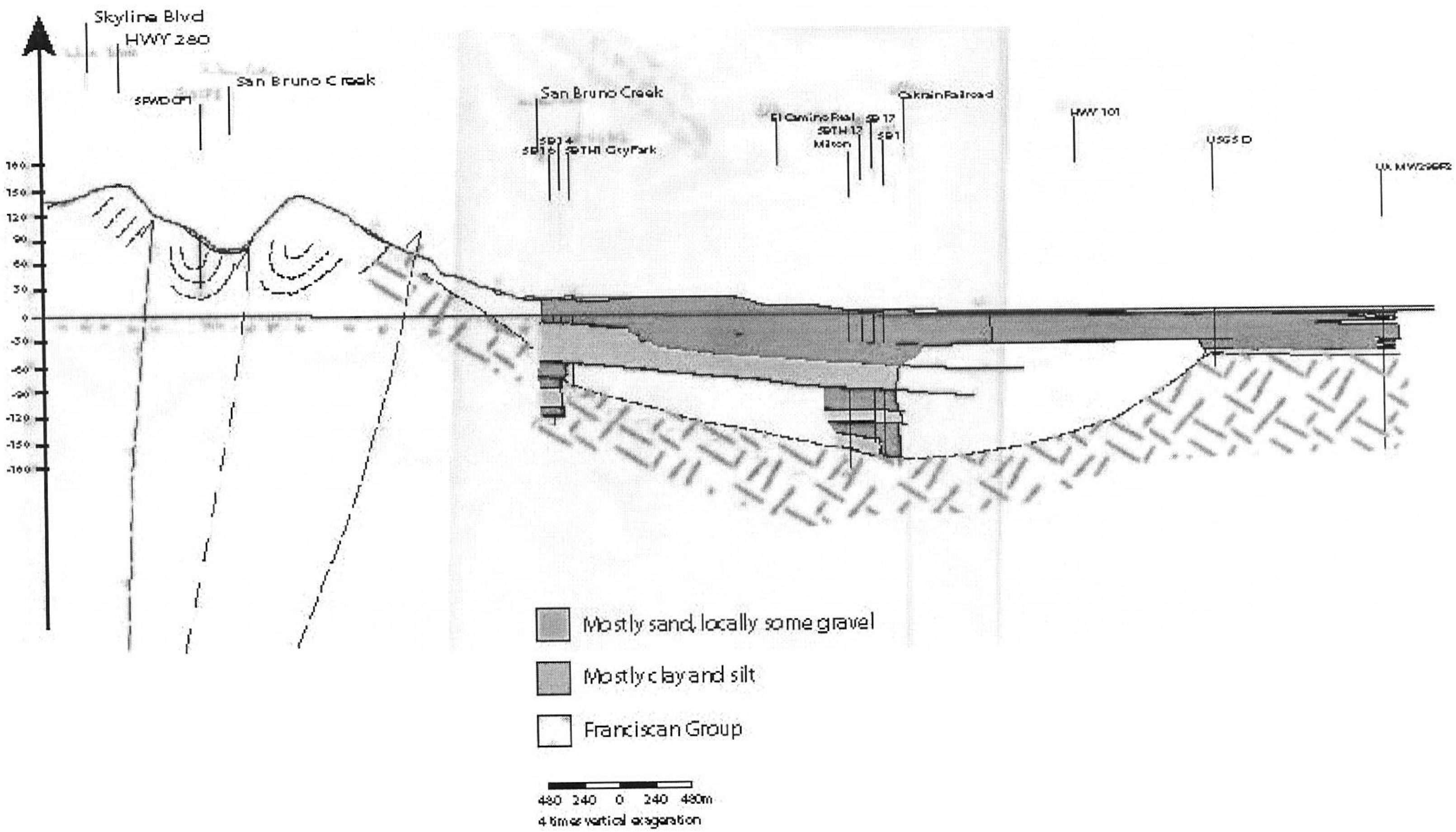

COLLUMNAR SECTION AND FACIES
LITHOLOGIC UNIT
SEQUENCE
HYDROSTRA-TIGRAPHIC UNITS
STRATI-GRAPHIC NAME
ASHES AND DISCONFORMITIES
SEDIMENT PROVENANCE
BATHYMETRY AND TECTONIC ACTIVITY
AGE
(m.y.)
M E R C E D
F R A N C I S C A N
M
I
A
18
TRANSGRESSIVE
REGRESSIVE
CYCLES
R
N
E
I R V I N G T O N I A N
P L E I S T O C E N E
0.7- 0.8
1.2- 2.1

COLLUMNAR SECTION AND FACIES	LITOLOGIC UNIT	SEQUENCE	HYDROSTRA-TIGRAPHIC UNITS	STRATI-GRAPHIC NAME	ASHES AND DISCONFORMITIES	SEDIMENT PROVENANCE	BATHYMETRY AND TECTONIC ACTIVITY	AGE (m.y.)
				M E R C E D		S C A N	M A R I N E 18 TRANSGRESSIVE REGRESSIVE CYCLES	IRVINGTONIAN 1.8-2.6 B L A N C A N 2.2-3.6 2.3-4.3 2.4-4.8 P L I O C E N E
							SAN ANDREAS FAULT	
								EQUIVALENT TO ETCHE GOIN FORMATION N E


A
A'
SW
NE
150
120
90
60
30
0
-30
-60
-90
-120
-150
-180
Thornton Beach Landslide
Skyline Blvd
Anticline
Rockland Ash at OCC
OCC8
OCC7
OCC6
Lake Merced Blvd
SFGC1951 well
SFGC USGS MW
SFGC1
19th Ave
Oceanview Park
Alemany Blvd
Mostly sand, locally some gravel
Mostly clay and silt
Franciscan Group
480 240 0 240 480m
4 times vertical exageration


B
B'
SW
NE
(m)
210
180
150
120
90
60
30
0
-30
-60
-90
-120
-150
-180
Lynvale Ct.
Skyline Blvd.
Rockland Ash Sequence 5
Serra Fault
Westlake Well
Lake Merced Country Club 2
HWY 280
DC10
Mostly sand, locally some gravel
Mostly clay and silt
Franciscan Group
480 240 0 240 480m
4 times vertical exageration


C
C'
SW
NE
(m)
210
180
150
120
90
60
30
0
-30
-60
-90
-120
-150
-180
Skyline Blvd.
San Andreas Fault
Gellert Blvd.
HWY 280
2300 Westborough MW4
2296 Westborough MW1
Serra Fault
California Golf Club 6
El Camino Real
Colma Creek
BART SFO 28
SS-1-17
SS-1-20
Mostly sand, locally some gravel
Mostly clay and silt
Franciscan Group
Well
Water level
Screen interval
480 240 0 240 480m
4 times vertical exageration


Skyline Blvd
HWY 280
SPWDCP1
San Bruno Creek
San Bruno Creek
SP14
SP16
SPTH1 CityPark
El Camino Real
SPTH17
Milton
SP17
SP1
Caltrain Railroad
HWY 101
USGS D
UK MW29BR2
180
150
120
90
60
30
0
-30
-60
-90
-120
-150
-180
Mostly sand, locally some gravel
Mostly clay and silt
Franciscan Group
480 240 0 240 480m
4 times vertical exageration