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# A critical physical geography of urban soil contamination

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ABSTRACT

Anthropogenic lead (Pb) is ubiquitous in urban soils given its widespread deposition over the course of the 19th and 20th centuries from a range of point- and non-point sources, including industrial waste and pollution, leaded paint, and automobile exhaust. While soil scientists and urban ecologists have documented soil Pb contamination in cities around the world, such analyses usually focus on proximal mechanisms but rarely consider more distal factors, notably the *social* processes mediating Pb accumulation in particular places. In this paper, I articulate a critical physical geography of urban soil Pb contamination that considers the dialectical co-production of soil processes and social processes. Using soil Pb contamination in the flatlands of Oakland, California as an empirical case, I integrate conventional quantitative geochemical mapping with theory and qualitative methods regularly employed in urban political ecology to explain the various spatio-temporal processes that bifurcated the city into flatlands and hills, a topography that is as much social as it is physical, and one that is fundamental to differentiated soil Pb concentrations and their disproportionate impact on low-income people of color. I demonstrate how understanding soil contamination through the lens of social metabolism – with particular attention to the materiality of the socio-natural hybrids emerging from processes of capitalist urbanization – can complement conventional analyses, while contributing to a "material politics of place" to support struggles for environmental justice.



## 1. Introduction

In early 2011, the United States Environmental Protection Agency (EPA) launched an Emergency Response project to bioremediate more than a hundred residential yards in West Oakland. In this low-income area of Oakland, California, the soils of residential yards averaged lead (Pb) concentrations of 843 ppm (mg $kg^{-1}$) of Pb, more than double the EPA's regulatory threshold of toxicity. The two-year, $4 million project's innovative technique involved amending soils with fishbone meal, a hydroxyapatite that complexes with soluble Pb to form the highly recalcitrant pyromorphite. Chemically "locked into place" and no longer bioavailable, the Pb in the soil of the remediated yards now poses little threat to human health (Barringer, 2011; Bohan, 2011; Freeman, 2012). The Fishbone Project is one of many ongoing efforts to remediate soil Pb contamination in American cities. Despite declines in the number of incidences of Pb poisoning over the past decades (Pirkle et al., 1994), the heavy metal persists in urban soils, worrying a range of publics. Urban agriculture's spike in popularity over the past several years has rekindled concerns about Pb contamination in gardens (Murphy, 2009; Seltenrich, 2011), and widespread reinvestment in the urban core has united developers, municipal leaders, health officials, and environmentalists in the push to remediate vacant lots and former industrial sites (Desfor and Keil, 2004).

Such concerns are understandable given Pb's insidious impacts on human health. Research has shown direct correlations between soil Pb and blood Pb levels (BLL), especially in children, who are particularly susceptible to Pb poisoning; while adults generally absorb less than 5% of ingested Pb, children absorb up to 50% (Laidlaw and Fillippelli, 2008; Mielke et al., 2007; Mielke and Reagan, 1998). Because Pb is similar in ionic structure to calcium (Ca), the body will utilize it in place of Ca when it is present in the bloodstream, altering or disrupting Ca-mediated processes. During childhood development, for example, Pb can be incorporated into bone. With a half-life of 30 or more years, Pb in such cases is then continually released into the bloodstream as the bone regenerates over time. When incorporated into the nervous system, it blocks glutamate receptors, interfering with chemical signals from the brain, as well as triggers apoptosis – programmed cell death – in neurons (Lidsky and Schneider, 2003; Needleman, 2004). The long-term impacts of Pb poisoning can therefore be severe. High BLL have been correlated with learning disabilities, attention deficit/hyperactivity disorder, and

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criminal behavior (Landrigan et al., 2002; Nevin, 2007; Wright et al., 2008).

A host of social factors, ranging from malnutrition to dilapidated housing, can increase Pb exposure, uptake, and absorption. Disproportionately impacting the poor and people of color, soil Pb contamination is thus an issue of environmental justice (Krieger and Higgins, 2002; Mielke et al., 2007; Sutton et al., 1995). Such concerns have given rise to a substantial body of soil analysis and geochemical mapping work (Mielke et al., 2007; Mitchell et al., 2014; Wu et al., 2010; Zhuo et al., 2012). Most of this important work is conventional in its approach, correlating geospatial and geochemical data to demonstrate the inequitable burden of soil Pb contamination and exposure. Only rarely, however, is such spatial analysis accompanied by the kind of theoretically informed, qualitative analysis familiar to most critical human geographers. Social scientists, on the other hand, have been generally "inattentive" to issues of soil degradation (Engel-Di Mauro, 2014, p. 1), and those who do engage with soils – political ecologists, for example – have tended to "focus on the social relations at the expense of what soil scientists have excelled at studying, the soils themselves" (Engel-Di Mauro, 2014, p. 5).

Critical physical geography (CPG) is one possible approach to overcoming the limitations of previous soil contamination research. Fundamentally concerned with the co-production of the biogeophysical and the social, as well as its implications for social justice, CPG

> requires critical human geographers to engage substantively with the physical sciences and the importance of the material environment in shaping social relations, while expanding physical geographers' exposure to and understanding of the power relations and human practices that shape physical systems and their own research practices (Lave et al., 2014, p. 4).

Echoing interventions in physical geography calling for the integration of insights from human geography (Tadaki et al., 2012; Wilcock et al., 2013), recent CPG contributions (cf Carey, 2010; Doyle et al., 2013; Lave and Lutz, 2014; Simon, 2014; Tadaki et al., 2014) respond to perennial calls in geography and other disciplines for an integrated science that takes seriously the interrelations between the social and the biophysical. Furthermore, CPG has the potential to move beyond the conventional "impact model" of human drivers of urban biogeochemical change (cf Grimm et al., 2008; Kaye et al., 2006; Pickett et al., 2011) by explicitly addressing the distal social processes mediating proximal soil disturbance, recognizing that "socio-biophysical landscapes are as much the product of unequal power relations, histories of colonialism, and racial and gender disparities as they are of hydrology, ecology, and climate change" (Lave et al., 2014, p. 3).

How, then, might a CPG approach provide new insights into the socio-spatial origins and impacts of urban soil Pb? In this paper, I attempt to answer this questions by laying the groundwork for a CPG of urban soil contamination, one that complements conventional quantitative soil science and geospatial analysis with theory and qualitative methods from urban political ecology (UPE). I begin the paper with brief overviews of Pb contamination and urban soils, then suggest how insights from UPE – notably the interrelated concepts of social metabolism, hybridity, and materiality – might inform a CPG of urban soil Pb. To illustrate this integrated framework, I present the example of soil Pb pollution in the flatlands of Oakland, California. After a preliminary quantitative analysis to explain the scale and scope of contamination, I turn to archival and secondary-source materials to produce a qualitative historical narrative of the socio-ecological processes that bifurcated the city into flatlands and hills, a topography that is as much physical as it is social. I describe how ebbs and flows of capital have resulted in disproportionate concentrations of various forms of Pb in the soils of the flatlands. My goal here is not to model or quantify these distal processes; rather, I hope to demonstrate how a CPG approach can provide a deeper socio-spatial understanding of urban soil Pb contamination, which, as I discuss in the conclusion, might articulate with a more radical – and material – politics of place.

## 2. Rethinking urban soil lead

### 2.1. Anthropogenic lead

The presence of anthropogenic Pb in the soil is not new; humans have been extracting Pb from the Earth for thousands of years. Beginning in the Copper Age, and increasing in the subsequent Bronze and Iron Ages, Pb was mined for use in various metal wares. Released into the atmosphere as a byproduct of smelting, its deposition on soils near and far is dependent on proximity to the source and particle size, as well as on the suite of environmental factors that affect air currents, from temperature to topography. With the advent of coinage and plumbing, the extraction, atmospheric emission, and deposition of Pb rose steadily with time, aside from a drop following the decline of the Roman Empire. With the Industrial Revolution, however, Pb extraction and pollution soared exponentially. The scale of Pb deposition – from mine tailings, factory waste, and airborne particles – increased in step with the expansion of industry. Taller smokestacks and new Pb-based technologies led to wider dispersion and diffusion (Nriagu, 1998).

In addition to Pb from industrial production, other sources of urban soil Pb pollution are related to consumption. Old batteries, solder, and plumbing added to soil Pb levels, but Pb's use as a gasoline additive over seven decades of the 20th century is the primary reason for its ubiquity in urban areas (Davies, 1995; Kabata-Pendias, 2011). Beginning in 1923, the use of tetraethyl Pb (TEL) as an anti-knock additive to gasoline gave a boost to anthropogenic Pb levels worldwide—the dominant source of Pb emissions had become mobile. Lead emissions from exhaust increased in the 1950s with rising automobile use, which itself was due in the US to a suite of interrelated factors: the expansion of the highway system, the decline of public transit, suburbanization, and a rise in real wages and consumption in the post-war Keynesian economy (Paterson, 2007). Restrictions on benzene as an anti-knock additive, intensive lobbying by TEL manufacturers, and a gag order by the Federal Trade Commission restricting criticism of TEL, all further increased demand for the product. Despite growing evidence of its public health dangers, it was eventually used in more than 90% of gasoline sold in the US (Kitman, 2000; Nriagu, 1990; Oudijk, 2010). Between 1927 and 1994, American cars released an estimated 5.37 million metric tons (Mg) of Pb into the atmosphere. Emissions in the US peaked around 1970 at more than 200,000 Mg per year, almost half of global Pb emissions (Mielke et al., 2010). In the 1980s, the annual median atmospheric deposition of Pb in North America was 4.26 kg $ha^{-1}$, much of which came from vehicle exhaust (Sposito and Page, 1984).

House paint is the other principal source of soil Pb in cities. Over 6 million Mg of Pb were used in paint in the US between the 1880s and the late 1970s, peaking at 1.2 million Mg used in the 1920s. Even though Pb concentrations in paint declined steeply by mid-century, high levels of Pb remain on the interior and exterior walls of houses to this day. One study estimated that lead paint covers 2.08 million $km^2$ – roughly a third of the total area of the US – of exterior surfaces of housing stock in the United States, or an average of 92.5 $m^2$ of lead-based paint per housing unit (Jacobs et al., 2002; Mielke and Reagan, 1998).

**Table 1**
Soil Pb concentrations found in urban and rural settings in selected US studies.

| Location | Total soil Pb[a] | | Sampling depth (cm) | Reference |
|---|---|---|---|---|
| | (mg kg$^{-1}$ | ±S.D.) | | |
| *Geogenic levels* | | | | |
| Oakland hills | 14.2 | ±4.4 | n.r. | City of Oakland (n.d.) |
| California | 23 | (med.) | 5–15 | Goldhaber et al. (2009) |
| Western US | 17 | ±1.8 | 20 | Shacklette and Boerngen (1984) |
| Eastern US | 14 | ±2.0 | 20 | Shacklette and Boerngen (1984) |
| Earth's crust | 14.8 | n.r. | n.r. | Wedepohl (1995) |
| *Urban areas* | | | | |
| Cleveland, OH | 123 | (med.) | 10–12 | Sharma et al. (2014) |
| Columbus, OH | 334 | (med.) | 10–12 | Sharma et al. (2014) |
| Los Angeles, CA | 181 | ±463 | 0–3 | Wu et al. (2010) |
| Lubbock, TX | 41.8 | ±4.9[b] | 0–2 | Brown et al. (2008) |
| Miami, FL | 152 | ±169 | 0–20 | Chirenje et al. (2004) |
| Phoenix, AZ | 27.6 | ±21.4 | 0–10 | Zhuo et al. (2012) |

n.r. = not reported; med. = median value, no standard deviation.
[a] Reported value is the arithmetic mean concentration unless otherwise noted.
[b] Reported value is standard error.

As the devastating impacts of Pb on public health came into focus by the mid-twentieth century, efforts to reduce exposure to Pb slowly gained traction. There was a gradual phase-down of Pb additives in gas beginning in 1975. In 1984 the US Senate passed the Airborne Lead Reduction Act, leading to a ten-year phase-out of leaded gas that took effect in January 1986. A total federal ban went into effect in 1996, four years after a statewide ban in California. Leaded paint was also curtailed by acts of Congress. Lower limits were set on interior house paint beginning in the 1940s; in the early 1970s, similar limits were set for external paint. The Consumer Product Safety Act of 1977 banned the sale of paint with more than 0.06% Pb content (Kitman, 2000; Nriagu, 1990).

Thanks to the gradual phase-out of leaded fuels and paints, anthropogenic deposition of Pb began to decline in the late 1970s (Jacobs et al., 2002; Sutton et al., 1995). Working in tandem with the rise of Pb poisoning prevention initiatives, these regulatory changes resulted in declines in blood Pb levels in children and can be considered a success story in environmental policy (Bridbord and Hanson, 2009; Levin et al., 2008). But while contemporary deposition of Pb has ebbed, historic deposition nevertheless continues to play an active role in cities; urban soil levels around the country are significantly higher than geogenic "background" soil Pb levels (see Table 1). In their recent meta-analysis of 84 soil Pb studies conducted between 1970 and 2012 in 62 US cities, Datko-Williams et al. (2014) found no significant change in soil Pb levels; concentrations were most closely related to proximity to the city center and population density, likely a result of leaded paint. Indeed, much of the Pb from exterior paint has gradually ended up in the soil: 52% of houses built before 1978 have yard soil Pb levels over the EPA threshold of 400 mg kg$^{-1}$ (Jacobs et al., 2002). As paint flakes off with age or is removed by scraping or sandblasting, small fragments contaminate the soil (Mielke et al., 1984; Sutton et al., 1995).

The presence, patterns, and persistence of Pb in urban soils are not only a function of its anthropogenic origins, however, but also of the physico-chemical characteristics of the soils themselves. I turn briefly to current understandings of urban soils before moving on to a discussion of what a CPG of urban soil Pb contamination might entail.

### 2.2. Urban soils

As the interface between the atmosphere, biosphere, lithosphere, and hydrosphere, the pedosphere – i.e. soil – is a complex natural body consisting of air, water, microorganisms, decaying organic matter, and unconsolidated, weathered minerals derived from underlying parent material or bedrock. Effland and Pouyat (1997, p. 217) characterize *urban* soils as "a continuum of 'human-altered' soil bodies intermixed with discrete islands of unaltered 'natural' soil bodies." The international World Reference Base for Soil Resources (WRB) generally classifies such soils as *Technosols*, soils that "contain a significant amount of ... something in the soil recognizably made or extracted from the earth by humans" (IUSS Working Group WRB, 2006, pp. 95–96). A prefix identifies a Technosol's dominant parent material: *ekranic* (manufactured hard rock, e.g., pavement); *garbic* (organic waste material); *spolic* (industrial waste, such as mine spoils, dredging, and rubble); and *urbic* ("rubble and refuse of human settlement").[1] A variety of anthropogenic disturbances, including road construction, the extraction or addition of fill during construction, which may include not only soil excavated from foundations or dredging, but also fabricated materials, such as crushed building materials (e.g. bricks, drywall, concrete), all impact soil composition and development (Effland and Pouyat, 1997). Pickett and Cadenasso (2009) note that such disturbances can be systematic (e.g. riparian restoration, construction, and gardens) and/or random (e.g. differential erosion, sedimentation, and weathering due to a particular land use). Random change may occur due to weathering or differential erosion following a systematic, anthropogenic disturbance; conversely, a soil profile shaped by random change can be disturbed in a systematic fashion.

With these disturbances (as well as via natural soil losses unrelated to disturbance), parent materials are mixed and the mineral composition of the soils transformed, ultimately impacting how Pb and other contaminants become part of the soil, i.e., what sort of chemical bonding or adsorption occurs. Disturbances also impact a range of biophysicochemical processes that mediate the rate of chemical weathering of these new complexes. New parent

[1] Soil categories that distinguish human impacts are inherently problematic, as they maintain a human-nature dualism and privilege capitalist societies with "soil-forming factor status, while other societies, by default, become part of 'natural' soils" (Engel-Di Mauro, 2014, p. 30). With this caution firmly in mind, I use the WRB category "Technosol" and its prefixes only to describe the dominance of a particular parent material in a particular soil complex in a particular space, and to distinguish it from adjacent soils that have been less-disturbed by processes of capitalist urbanization. I've opted to use WRB over US taxonomy here for much the same reason that one might use metric (SI) units instead of US/Imperial measures (i.e., to speak to a more international audience), but also because of the greater specificity of the WRB prefixes regarding of the origins of the parent material.

material can change a soil's pH, cation exchange capacity, water-holding capacity, or microbial populations, for example, thereby slowing down or speeding up rates of hydrolysis and protonation (Brady and Weil, 2002; Sposito, 2008).

Urban soil variation is often clearly linked to particular socio-technical regimes. In a Detroit study, for example, researchers found that fill material tended to be locally derived and thin (less than 40 cm) prior to the 1929 advent of diesel-powered earth-moving equipment, whereas fill applied later was thicker (60–100 cm), highly compacted, and comprised of offsite material. Further noting that "random variations in parent material overshadow the effects of time" (Howard et al., 2013, p. 10), they identify high levels of carbonate and the development of calcic horizons associated with the weathering of building mortar fragments by nitrifying soil bacteria, as well as iron oxide-cemented crusts surrounding nineteenth century wrought-iron nails.

Clearly, soils have no "predetermined evolutions" (Swidler, 2009, p. 2). Rather, contemporary soil change is nested within different spatiotemporal "ecosystems" operating at longer scales (Richter, 2007; Richter and Markewitz, 2001). Soils "accrue features over their lifetimes" (Richter and Yaalon, 2012, p. 766) via variable anthropogenic and geogenic processes. While soil scientists and urban ecologists have taken the lead on identifying and quantifying human *impacts on* soils, understanding how social and biogeophysical processes *co-evolve* is considerably less clear. Alberti et al. (2003) caution that models using socioeconomic variables as a proxy for human activity oversimplify complex ecological processes, but I would add that they are also unable to account for the distal *social* processes – political economies, behavioral logics, power relations – that mediate these impacts in a socio-spatially differentiated manner.

Heeding calls for an interdisciplinary "anthropedology" (Richter et al., 2011; Richter and Yaalon, 2012), I argue then for the need to integrate theoretically informed, qualitative understandings of historically contingent social processes, rather than trying to incorporate an ever more nuanced suite of socioeconomic variables into a regression model. As Swidler (2009, p. 6) contends, "only by learning human history and the full range of human activity can relevant questions even be posed for soil research." Researchers must do more than simply identify anthropogenic processes; they must also recognize that "soil is a manifestation of social history, an embodiment of social dynamics" (Swidler, 2009, p. 7). In short, we must examine both "soil memory" (Targulian and Goryachkin, 2004; Wells, 2006) – the materially encoded physical, chemical, and biological effects of human activity – *and* the social processes and relations underwriting such activity. This is precisely the kind of work that a CPG of soil Pb might help us with. I now address how urban political ecology (UPE) might inform such an approach.

### 2.3. Engaging urban political ecology

For over a decade, work in UPE has helped critical geographers to overcome false dualisms such as city/nature, urban/rural, and nature/society by re-conceiving of cities as co-produced, socio-ecological systems (Braun, 2005; Heynen et al., 2006; Keil, 2003; Loftus, 2012). Urban political ecology proposes that "nature does not stop at the foundations: the city is constitutively social *and* natural from the bottom to the top, and urban nature is just as political as urban society" (Wachsmuth, 2012, p. 516). A set of interrelated concepts central to UPE are particular useful for a CPG of urban soil Pb: metabolism, socio-natural hybrids, and materiality.

In UPE, metabolism describes the "circulatory processes that underpin the transformation of nature into essential commodities such as food, energy and potable water" (Gandy, 2004: 364), and is fundamental to the dialectical co-evolution of social relations and biophysical processes. Drawing on both Marxian political economy and post-structuralist frameworks (e.g. actor-networks and assemblage theory), UPE holds metabolism to be "a dynamic process by which new sociospatial formations, intertwinings of materials, and collaborative enmeshing of social nature emerge and present themselves and are explicitly created through human labor and non-human processes simultaneously" (Heynen, 2014, p. 599).

Marx's description of the "social metabolism" of the biogeophysical environment lies at the root of this analytic. For Marx, "Labor is, first of all, a process between man [sic] and nature, a process by which man, through his own actions, mediates, regulates and controls the metabolism between himself and nature" (Marx, 1976, p. 283). Only through labor can one derive sustenance from soil, water, or air. The subsumption of human labor by capitalist modes of production (e.g. the transition from subsistence to wage labor), however, radically *rescaled* this metabolism. Rarely do we produce our own food or draw water with our own hands; instead, we exchange our labor power for wages on a market mediated by global forces. With fewer and fewer exceptions, contemporary human metabolism – both organismal and social – primarily occurs with the aid of spatio-temporal subsidies – e.g. food shipped from thousands of miles away, grown using oil drilled from strata millions of years old – mobilized via a capitalist socio-technical assemblage of material infrastructure spanning the oceans, continents, and satellite orbits (McClintock, 2010; Ogden et al., 2013).

The relationship is a dialectical one, as transformation of the biogeophysical environment modifies social relations and humans themselves (Engel-Di Mauro, 2014; Harvey, 2006; Levins and Lewontin, 1985; Loftus, 2012; Marx, 1976). Urban political ecologists thus treat nature as *internal* to urban processes, rather than as an opposing force, and urbanization as "a metabolic circulatory process ... organized through socially articulated networks and conduits" (Swyngedouw, 2006a, p. 35), a process of socio-ecological co-production that is "hybridized and historically contingent" (Gandy, 2004, 364). This perspective not only diverges from conventional urban ecology work whose treatment of socio-ecological feedbacks depends on a false ontological human-nature binary, but also deviates somewhat from two dominant approaches used by critical geographers: the historical materialist "production of nature" lens and the post-structuralist "social construction of nature" lens, both of which "risk mobilizing (and, therefore, shoring up rather than transcending) conventional dualistic conceptions of nature and society" (Bakker and Bridge, 2006, p. 11). By focusing on the "the matter of matter" (Fitzsimmons, 1989), UPE has demonstrated how the materiality of such hybrids can shape the direction and outcomes of future processes, thus playing a crucial role in the dialectic of socio-natural co-production (Braun, 2005; Lawhon, 2013; Perkins, 2007; Swyngedouw, 2006b). In this vein, I argue that examining the socially articulated and historically contingent nature of metabolism, as well as the materiality of the hybrid socio-natures that result, is key to understanding soil contamination.

If labor is the means through which humans transform their surroundings, then understanding social metabolism – and its integument with soil processes – demands that we extend our analysis to historically specific processes of capitalist urbanization mediating labor power, production, and consumption. In cities, the influx of capital is visibly inscribed on the landscape in the form of buildings and infrastructure (e.g. roads, bridges, power lines, rail lines, sewers). During historical moments of capital overaccumulation following economic booms, surplus is invested in such immobile or "fixed" capital. During economic downturns, as capital retreats from urban industrial and residential zones, the built environment deteriorates, often to such a great degree that it precludes further investment. Rents fall, unemployment rises, and labor and fixed capital are devalued (Harvey, 1989, 2007; Smith, 2008).

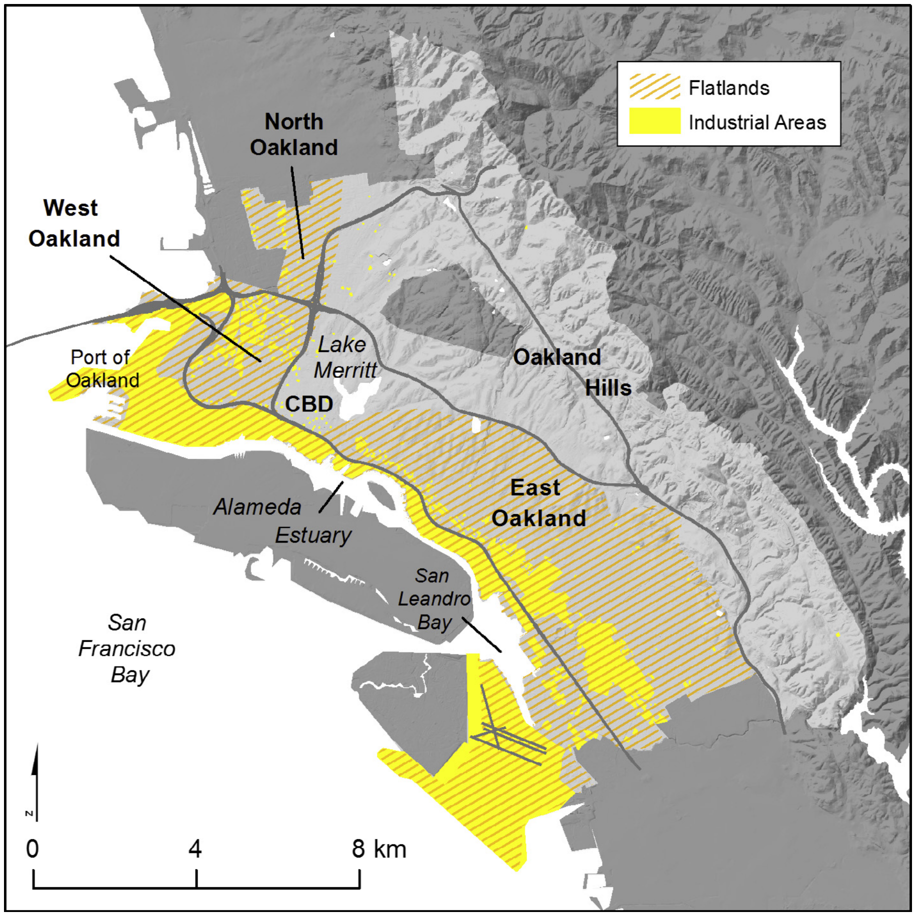


**Fig. 1.** Oakland, California. With a population of ~392,000 (2010), it is one of three core cities in the San Francisco Bay Area metropolis (2010 pop. ~7 million). The Oakland hills are one of California's Coast Ranges, uplifted from the Hayward and Moraga faults. The Central Business District (CBD) is located to the west of Lake Merritt. Note that most of the industry is located in the flatlands along the water, and that freeways demarcate the Oakland hills.

The circulation of capital is mediated and delineated through planning, policy, property taxes, bond ratings, political boundaries, and economic redevelopment zones, among other things, all of which ultimately shape urban land uses and their ecologies in a historically contingent manner (Hackworth, 2007; Harvey, 1989). Whether or not they were crafted with intention, these structures effectively demarcate flows of investment and disinvestment, and even "quarantine" devaluation to prevent its impacts from bleeding over. This process of "demarcated devaluation" (McClintock, 2011) has historically been highly racialized, through exclusionary zoning, redlining, and neighborhood covenants (Boone et al., 2009; Goodling et al., 2015; Sugrue, 2005). Capital's transformation of the physical environment thus occurs in an uneven manner (Harvey, 2007; Smith, 2008), the contemporary cityscape a map of previous cycles of capital accumulation and devaluation, a palimpsest of construction, decay, and renewal. The resulting differential landscape has socio-ecological ramifications; improvements to socio-ecological conditions in one part of a city often result in socio-ecological deterioration elsewhere, whether in the same city or far afield (Swyngedouw and Heynen, 2003).

By examining city-scale soil Pb patterns in relation to a history of intensifying and extensifying social metabolism, a CPG approach can help us better interpret differential soil processes – disturbances, additions, translocation, and transformations – while also revealing how these spatial patterns are linked to racist ideology and to larger-scale political economies of boosterism and speculation, of economic agglomeration and restructuring. Working across spatial and temporal scales, a CPG thus makes sense of biogeophysical changes through a "critique of power, inequality, injustice and exploitation, at once within and among cities" (Brenner, 2009, p. 198). But it also attends to how these changes, in turn, transform social processes. By taking seriously the materiality of an emergent socio-nature – in this case, soil Pb – a CPG refocuses the analytical lens of metabolism to more fully encompass biogeophysical aspects of the socio-natural dialectic (Bakker and Bridge, 2006; Engel-Di Mauro, 2014; Fitzsimmons, 1989).

In what follows, I illustrate what a CPG approach might bring to a case study of soil contamination in post-industrial Oakland, California, USA (see Fig. 1). Integrated into a broader explanation of Oakland's uneven development, the spatial patterns of soil Pb concentrations provide a stark illustration of how social metabolism of the landscape occurs differentially, with material consequences for soils and humans alike.

## 3. Understanding soil lead contamination in the Oakland flatlands

### *3.1. Scratching the surface: Results of laboratory and geospatial analysis*

I begin by drawing on quantitative soil data collected in Oakland in 2009 and 2010 (see Table 2 and Supplementary Geospatial Data). Detailed methods related to field sampling,

**Table 2**
Physico-chemical characteristics of soil samples ($n = 50$).

| | Pb (mg kg$^{-1}$) | Ca (mg kg$^{-1}$) | P (mg kg$^{-1}$) | C (mg kg$^{-1}$) | N (mg kg$^{-1}$) | C/N | pH | Sand (%) | Silt (%) | Clay (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| Mean | 181 | 6900 | 743 | 45,074 | 3359 | 13.6 | 6.7 | 49 | 26 | 24 |
| S.E. | 51 | 417 | 55 | 2807 | 202 | 0.3 | 0.1 | 2.2 | 2.5 | 1.2 |
| Median | 59 | 6435 | 675 | 44,645 | 3416 | 13.1 | 6.7 | 48 | 27 | 25 |
| Min | 13 | 2330 | 310 | 14,269 | 680 | 10.3 | 6.0 | 18 | 3 | 7 |
| Max | 2262 | 15,520 | 1990 | 95,861 | 7117 | 21.0 | 7.6 | 86 | 52 | 42 |
| CV | 199.5 | 42.8 | 51.9 | 44.0 | 42.6 | 16.5 | 6.1 | 32.6 | 39.4 | 34.0 |

**Table 3**
Mean soil Pb levels (mg kg$^{-1}$) by geographic region in Oakland, California.

| Region | $n$ | Total Pb (mg kg$^{-1}$) | | | |
|---|---|---|---|---|---|
| | | Mean ± S.E. | Median | Min | Max |
| North | 8 | 116 ± 35.1 | 76 | 25 | 286 |
| West | 8 | 573 ± 273.2 | 182 | 44 | 2262 |
| Central | 12 | 145 ± 31.0 | 131 | 30 | 370 |
| East | 9 | 156 ± 78.7 | 62 | 13 | 756 |
| Hills | 13 | 31 ± 5.1 | 27 | 18 | 88 |
| Total | 50 | 181 ± 51.1 | 58.5 | 13 | 2262 |

laboratory methods, and geospatial analysis can be found in Appendix A and in other publications (McClintock, 2012; McClintock et al., 2013).

Results of field sampling and laboratory analysis indicate that soil Pb concentrations are significantly higher in the flatlands of West Oakland (the oldest part of the city) and lowest in the Oakland hills (see Table 3), where Pb levels are the same as geogenic background levels. The resulting geochemical map of soil Pb in Oakland illustrates the stark socio-ecological divide between the low-income flatlands and more affluent – and white – Oakland hills (see Fig. 2). On average, 2.1% of the city's children and youth under 21 have unsafe blood lead levels between 4.5 and 9.4 μg dL$^{-1}$; 0.5% of children with blood lead levels > 9.5 μg dL$^{-1}$ (Healthy Homes Department, 2014). As Fig. 2 illustrates, most of these cases are concentrated in flatlands neighborhoods, supporting a body of geospatial studies revealing the disproportionate impact of Pb contamination on low-income communities of color (e.g. Mielke et al., 2007; Zhuo et al., 2012). High soil Pb levels correspond spatially with elevated blood Pb levels, non-white populations, and poverty.

Moreover, Pb levels tend to be higher in residential and industrial zones than in open space, higher in gardens and vacant lots, and lower in parks and vegetated open space (McClintock, 2012). As Table 4 shows, a number of social variables correlate with soil

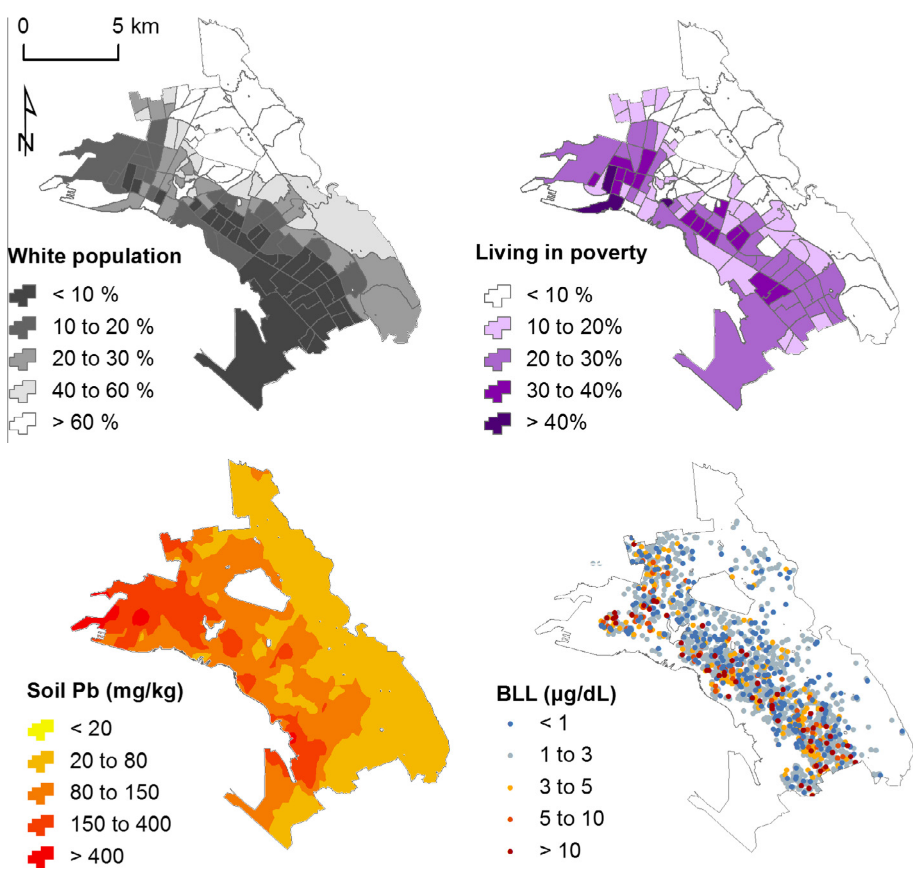


**Fig. 2.** Socioecological differentiation between Oakland's hill and flatlands. White population (top left) and population living in poverty (top right; data: American Community Survey 2011). Soil Pb concentrations (bottom left; data: this study) over 400 mg kg$^{-1}$ exceed the federal screening threshold for safe soil and are concentrated in West Oakland and elsewhere in the flatlands. Blood Pb concentrations (bottom right; data: Alameda County Lead Poisoning Prevention Program) over safe levels of 5 μg dL$^{-1}$ are similarly concentrated in the flatlands.

**Table 4**
Pairwise correlation of selected socioeconomic variables and soil Pb ($n = 113$).

| Variable | Distance to major road | Density of pre-1940s housing | Percent renter-owned housing | Year built | Median HH income | Percent white pop. | Pop. density |
|---|---|---|---|---|---|---|---|
| Log Pb | −0.293* | 0.354* | 0.418* | 0.038 | −0.251* | −0.147 | 0.270* |
| Distance to major road | | −0.104 | −0.240* | −0.096 | 0.045 | −0.086 | −0.159 |
| Density of pre-1940s housing | | | 0.508* | 0.250* | −0.231* | −0.081 | 0.649* |
| Percent renter-owned housing | | | | 0.453* | −0.425* | −0.218* | 0.632* |
| Year built | | | | | 0.299* | 0.256* | 0.322* |
| Median household income | | | | | | 0.806* | −0.276* |
| Percent white population | | | | | | | −0.101 |

* $p < 0.05$.

**Table 5**
Spatial regression of log total soil Pb on soil chemical and anthropogenic factors.

| Variable | Coefficient |
|---|---|
| Spatial lag ($\rho$) | 0.139 |
| Constant | −1.203 |
| C/N | 0.146** |
| Log P | 0.665** |
| Log Ca | −0.412** |
| Pre-1940s housing density | 0.013* |
| Distance to major roads | 2.888e−06 |
| Percent renter-owned | 0.001 |
| df | 42 |
| $R^2$ | 0.790 |
| Log likelihood | 2.833 |
| $\sigma^2$ | 0.052 |
| AIC | 10.334 |

* $p < 0.05$.
** $p < 0.01$.

Pb levels, including the density of pre-1940s housing, the percentage of housing units occupied by renters, and distance to major roads. However, when combined into a single spatial regression model, only the density of old housing stock is as significant an explanatory variable as the soil chemical characteristics most commonly associated with Pb (see Table 5). As I will discuss in greater detail in the next section, Pb is commonly found as the mineral pyromorphite, where it is complexed with phosphorus (P). It is also frequently complexed with carbon (measured here using the carbon-to-nitrogen [C/N] ratio) in the form of the Pb carbonate cerussite, often substituting for Ca (hence the negative regression coefficient for Ca in the model).

The analysis presented in Table 5 suggests that the city's housing stock is a primary source of soil Pb contamination in Oakland. Ninety-percent of housing structures in Oakland were built before 1979, two years before the ban on Pb-based exterior house paint went into effect, and more than a third of the city's structures were built in 1939 or earlier (US Census Bureau, 2000) when Pb concentrations in paint were at their highest. Well after the ban, leaded house paint continues to contaminate the soil as it flakes off, is scraped or sandblasted. Resuspension of soil-borne Pb particulates in the air can also contaminate nearby uncontaminated soil, or remain in the air, eventually infiltrating into houses where, along with soil tracked in on shoes, it is incorporated into household dust (Clark et al., 2006; Laidlaw and Fillippelli, 2008; Layton and Beamer, 2009). A 1995 study in Oakland found that nearly half of front or backyards sampled had soil Pb levels higher than 1000 mg kg$^{-1}$, classified as hazardous waste at the time of study. At sample sites immediately adjacent to a house, levels measured higher than 10,000 mg kg$^{-1}$. Lead levels correlated strongly with age of housing: 93% of homes built before 1920 had levels of 500 mg kg$^{-1}$ or above, while only 67% homes built between 1950 and 1970 had such levels (Sutton et al., 1995). Various studies have also attributed Pb contamination in the Bay Area to automobile exhaust (Hornberger et al., 1999; Hwang et al., 2009; Martens et al., 1973). Mielke et al. (2010) calculated that 31,922 Mg of Pb was emitted in the San Francisco/Oakland Metropolitan Area between 1950 and 1982.

Short of employing expensive isotope analysis or soil mineral spectroscopy to more precisely identify specific forms of Pb (which can be associated with particular historical uses), the above analysis suggests both the likely sources of contamination and soil chemical characteristics most associated with total Pb concentrations. This standard, surface layer quantitative assessment elucidates the scope and scale of soil Pb contamination in Oakland, as well as the inequitable socio-spatial distribution of Pb across the city. But a CPG only uses these data as a starting point. To complement this quantitative analysis and to attempt to establish relationships between proximal and distal processes, I next draw on the theory outlined above and employ qualitative methods, notably archival research (newspapers, government documents, photos, and maps), to construct a broader socio-natural history of the city's soils and Pb concentrations.[2] Before turning to an explanation of the distal social processes mediating patterns of contamination, I briefly discuss soil Pb's multiple forms, each with particular material characteristics that increase or diminish its toxicity and persistence in the soil.

### 3.2. Species of soil lead

Total Pb, the overall concentration of Pb in a particular soil, is an aggregate measure that tells us little about the forms or "species" of Pb present. In the soil, Pb exists in a range of solid-phase forms that weather in an integrated, simultaneous, and interdependent manner. Its primary mineral form is galena, or Pb sulfide, an ore form that ultimately weathers to secondary minerals such as anglesite ($PbSO_4$), pyromorphite [$PbCl_2{\cdot}3Pb_3(PO_4)$], and mimetesite [$PbCl_2{\cdot}3Pb_3(AsO_4)_3$], cerussite ($PbCO_3$), and a variety of apatites, which then weather or precipitate into new Pb mineral complexes (Davies, 1982; Kabata-Pendias, 2011; Ponizovsky and Mironenko, 2001). These forms are highly stable under a middle range of pH and weather according to a predictable sequence. Rates of weathering are highly variable, however, due to variations in the surrounding physical and chemical environment. Physical processes (freezing, thawing, and bioturbation) accelerate chemical processes (hydrolysis and protonation). Further, weathering a not unilinear process; to maintain stoichiometric equilibrium, an individual Pb ion may flip-flop back and forth for years between different mineral forms, as it solubilizes, sorbs, and precipitates as part of a new mineral (Brady and Weil, 2002; Sposito, 2008).

Most anthropogenic Pb enters urban ecosystems in even more labile forms, and its transport and fate vividly illustrate processes of socio-ecological co-production occurring at various

[2] For land use histories of specific sites, see McClintock (2012).

spatiotemporal scales. Consider the possible path that Pb in Oakland may have taken, mediated by both social and natural processes, as it moved through a variety of hybrid forms. Originating in a galena deposit formed in Paleozoic dolostone in the Old Lead Belt of the Southeastern Missouri Mississippi Valley, it was perhaps extracted, crushed, slurried, and concentrated at a mine near Bonne Terre, Missouri sometime in the mid-1950s. It was then transported 40 km to the St. Joseph Lead Co. smelter in Herculaneum the sulfur was removed and the molten Pb refined and recast into an alloy (Kleeschulte, 2008). Ingots of the Pb-sodium alloy were then transported to a refinery, possibly the 378-acre Dupont's TEL plant outside of Antioch, California, built in 1955. Here they were reacted with chloroethane to synthesize TEL using a steam distillation process, then blended with the liquid halocarbons 1,2-dibromoethane and 1,2-dichloroethane. This form of Pb was then added to gasoline, transported by tanker truck to a gas station, where it was sold and used in an automobile engine driving through Oakland. On combustion, most of the Pb ions complexed immediately with the halocarbons, becoming volatile Pb halides – e.g. PbBr, PbBrCl, Pb(OH)Br, and $(PbO)_2PbBr_2$ – which could have remained airborne for as many as ten days (EPA, 2002). Upon their deposition on the soil surface, following some rainfall and bioturbation – by a backhoe, or even an earthworm – the Pb might have then replaced Ca through isomorphic substitution in calcium carbonate ($CaCO_3$) particles from stucco or mortar mixed into the soil at a residential construction site, forming a new carbonate such as cerussite ($PbCO_3$). Here it would remain relatively stable for decades (provided the pH remained relatively neutral), part of an urbic Technosol comprised of both anthropogenic artifacts and soil minerals weathered from Pleistocene alluvium. Unaware of the risk, a child today might repeatedly ingest vegetables grown in this soil, neglecting to scrub off the soil particles beforehand.[3] The cerussite clinging in the skin of the radish or beet or carrot would be dissolved by hydrochloric acid in her stomach, freeing the Pb for absorption into her bloodstream; the majority of absorbed Pb will eventually complex with osteoblasts forming her bone tissue, possibly to be re-released into her bloodstream over several decades.

We can imagine Pb following a similar trajectory as it moved from mine to paint factory to house (see Fig. 3), then to soil and to bloodstream, albeit in different hybrid forms along the way. Lead oxides (PbO, $PbO_2$, and $Pb_3O_4$) were historically used as a red pigment in paint, while the Pb carbonates hydrocerrusite – $2Pb(CO_3)_2{\cdot}Pb(OH)_2$ – and "white lead" – $(PbCO_3)_2{\cdot}Pb(OH)_2$ – were also commonly used as a white pigment in paints (Clark et al., 2006; Davies, 1995; Kabata-Pendias, 2011; Ponizovsky and Mironenko, 2001). Whatever pathway a particular Pb particle took in its journey from its point of origin to a soil in Oakland, social and biogeophysical processes mutually determined its particular hybrid forms, some of which less stable than others, and thus more easily taken up by human bodies. To explain the socio-spatial patterning of soil Pb, however, I turn now to a broad brushstroke history of the urbanization process – with particular attention to the inflows and outflows of capital that mediate social metabolism in a differential manner.

### 3.3. Unearthing distal factors, understanding spatial patterns

#### 3.3.1. Topographic base layers and early social metabolism

While analyzing multi-millennial scale processes may not be necessary to explain soil Pb deposition occurring at some point during the twentieth century, Oakland's bifurcated topography plays a key role in the geography of soil Pb contamination.[4] A quick snapshot of the physical geography – geomorphic and pedogenic – is therefore a useful starting place. A map of Oakland's geology reflects the multiple layers of geomorphic and anthropogenic processes that have defined the city's physical landscape and the creation of its soils (see Fig. 4a). East Bay topography is largely the result of tectonic processes. The movement of the Pacific Plate northward along the San Andreas Fault has created a network of semi-parallel strike-slip and thrust faults, including the local fault system which became active ~12 million years ago. Compression and uplift have produced the undulating, parallel ridges of the Coast Ranges, including the Oakland hills. Thrust upwards along the Hayward and Moraga faults over the past million years, they continue to rise, but have eroded away at a similar rate, exposing a palimpsest of overlying sedimentary and basement complex rocks, folded and faulted in a series of ridges (Sloan, 2006). Various forms of mass wasting—slumps, debris flow, rock fall, and creep—have contributed to the gradual erosion of the Oakland hills. The vast majority of Oakland's foothills and flatlands are therefore made up of this Pleistocene alluvium, with one broad alluvial fan stretching from North to East Oakland. Several creeks have historically drained the ridges, leaving more recent deposits of Holocene alluvium in their floodplains. Over time this massive fan of alluvium would weather to become the endogenous soils of the city's flatlands (see Fig. 4b), and the mineral lattices to which Pb might eventually adsorb or bond.

While primary pedogenesis has occurred at multi-millennial scales, understanding spatial patterns of contamination requires analysis of more recent human processes that have modified these base layers – and produced new ones – at shorter time scales. Anthropogenic soil changes unfolding over a "historical" timescale of thousands to hundreds of years (Richter, 2007) are generally related to subsistence activities, micro-scale pre-capitalist social metabolism of the landscape that led to differential physical and chemical weathering and erosion. At the time of the arrival of the Spanish in 1771, Chochenyo Ohlone-speaking populations (totaling between 10,000 and 20,000) practiced annual burning of underbrush to stimulate regrowth of plants and berries and to attract game (Keeley, 2005). New kinds of soil disturbance occurred over the ensuing fifty-year Mission Period; cattle and horses, a new source of anthropogenic bioturbation, compacted soils and introduced exotic annual grasses via their hooves and manure, and new vegetative species modified water infiltration, rates of weathering, and erosion. While rates of chemical weathering were changing due to these new disturbances, most soil Pb was likely geogenic, with the exception of scattered musket balls and pewter shavings.

Social metabolism in the East Bay became progressively more tied to wages and market exchange during the Rancho Period that followed. In 1820, the year before Mexican independence, the Spanish crown granted Luis Peralta 181 $km^2$ of land. Migrant Mexicans and local indigenous laborers managed crops and orchards dotting the Peralta's Rancho San Antonio, as well as the more than 8000 cattle and 2000 horses destined for both local and foreign markets (Bowman, 2001). This intensive grazing transformed the soil and vegetation, materially marking the new linkages to a market economy in the soil memory.

#### 3.3.2. New modes of production

American annexation of California in 1848 marked a new era, as did the arrival of Anglo squatters on Peralta lands. The scale and intensity of social metabolism increased as the population grew and capitalist land, labor, and commodity markets expanded. The

[3] It is important to note here that most Pb ingestion occurs when the soil itself is consumed. Uptake of labile Pb through plants' root systems is negligible given the size of its atomic radius and the acidic pH necessary in the soil solution for it to move into its ionic form.

[4] A geologic time scale is also useful in explaining the origins of the Pb itself, as the earlier description of Pb extraction demonstrates.


**Fig. 3.** A 1939 industry advertisement for white lead, a Pb carbonate ($2PbCO_3{\cdot}Pb(OH)_2$) widely used as a pigment in housepaint throughout the 20th century. This ad beautifully illustrates the distal social and scalar processes prefiguring soil Pb contamination – from Pb's extraction by a miner to its application by a house painter – while emphasizing Pb's material properties; its durable nature was its selling point, but also the reason for its persistence in urban soils. *Source: Architectural Forum*, May 1939, p. 39.

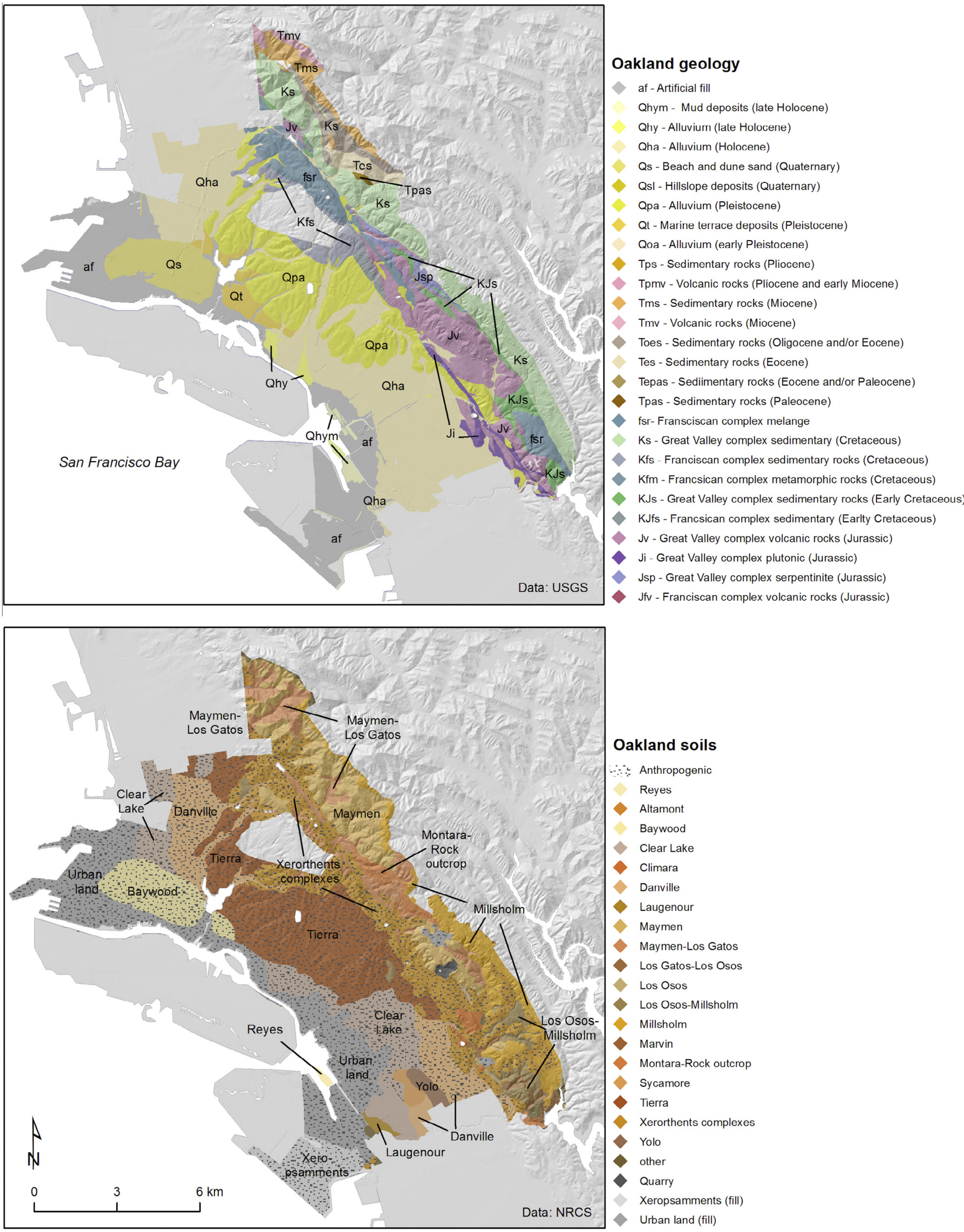


**Fig. 4.** (a) Oakland's geologic layers (top), which form the soil parent material for the city's (b) soil series (bottom). Soils series denoted as "anthropogenic" (indicated by the gray speckled pattern) are generally complexes of the underlying endogenous soil series and "urban land" (Welch, 1981), a heterogeneous mixture of urbic, garbic, spolic, and ekranic Technosols.

state legislature incorporated the nascent town of Oakland in 1852 at the western edge of the Rancho. Surveyors and speculators quickly platted and sold off home sites to the new arrivals west of Lake Merritt, while farms, ranches, and orchards soon crowded the outskirts of the fledgling town to the east and north. Construction of the Oakland terminus of the transcontinental railroad in 1869 accelerated the expansion of industry from San Francisco to the East Bay. By that year, sixteen factories ‘‘including sawmills, tanneries, slaughterhouses, dairies, a jute mill, a boot and shoe factory, flour mills, drydocks and a brewery’’ were actively processing the region's natural resources (Walker, 2001, p. 45). Industry and worker housing emerged primarily in West Oakland flatlands, between the downtown business district and the rail and shipping terminus (Bagwell, 1982; Scott, 1985; Walker, 2001).

Fixed capital – roads, housing, docks, shipyards, railroads, quarries, factories – transformed the grazing lands and oak groves of Rancho San Antonio, rapidly overwriting older layers of the soil palimpsest that had developed over much longer time scales. With population and industry growing at a rapid pace, and aided by the extension of streetcar lines, Oakland expanded northward and eastward through the flatlands, annexing surrounding communities. Expansion of the built environment and land speculation alike pushed livestock and agriculture off of prime flatlands real estate onto less valuable land, usually too steep for construction, marking a new socio-ecological differentiation: hills as the zone of extraction and flatlands as the zone of industrial production and center of population.

Speculators hoped to cash in on Oakland's proximity to San Francisco's bustling commercial center, making Oakland the first ‘‘edge city’’ in the Bay Area's ‘‘process of accretion’’ (Walker and Schafran, 2015, p. 14). The 1906 San Francisco earthquake was a boon for Oakland's population and economy. Housing went up rapidly to accommodate the seismic refugees, while development of vast tracts of land followed on the heels of timber extraction in the hills above (Simon and Dooling, 2013). One of the most powerful developers – and the nation's largest at the time – was The Realty Syndicate, which developed nearly 5300 ha in Oakland between 1895 and 1913 (Walker, 2001; Walker and Schafran, 2015). A 1910 ad for one of its subdivisions bluntly explains the process – and market logic – that transformed Oakland's hills and pastures into an eastwardly sprawling urban landscape (see Fig. 5): ‘‘Our idea in this is partly selfish. We own several million


**Fig. 5.** The inflow of residential capital in Oakland. Looking north from the same hilltop east of Lake Merritt in 1916 (top) and 1928 (bottom), we see the wholesale transformation – the social metabolism – of the underlying Tierra series soil (derived from fan of Pleistocene alluvium eroded from Oakland hills, visible in the distance) over the course of a decade. Photos courtesy of the Oakland Public Library.

dollars' worth of Oakland real estate… To sell it profitably we must either develop it to its fullest possibilities before we sell a foot of it, or we must, by some past achievement, assure and convince buyers that we WILL develop it" (The San Francisco Call 1910, 15). And convinced they were. The emergence of Oakland's vibrant housing sector drew a wealthy merchant class to the Oakland hills, a refuge "far removed from the dirt and turmoil of the work-a-day world" (a 1911 ad cited in Scott, 1985), imposing new social parameters onto the city's bifurcated topography.

Such Arcadian boosterism belied the industrial powerhouse reshaping socio-ecological processes in the flatlands below. Coarse fill material was deposited along the Alameda estuary and San Francisco Bay, becoming the most recent addition to the city's geologic palimpsest, as illustrated by the artificial fill (af) category in Fig. 4a. Industrial sources of Pb emerged throughout the flatlands along the water. North of Oakland, the Selby Smelter & Lead Works had become a principal source of atmospheric Pb in the East Bay as early as the 1870s. By 1908 pollution was so bad just across the Sacramento River that the Solano County Superior Court issued an injunction against the smelter for "liberating at and therefrom into the air sulphurous and other injurious and noxious gases and smoke … offensive to the senses so as to interfere with the comfortable enjoyment of life and property" (Holmes et al., 1915, p. 3). Foundries such as the Phoenix Iron Works in West Oakland likewise belched smoke laden with Pb and other heavy metals (Letzing, 2004; McClintock, 2012). The Allied Signal factory, with its 100-foot smokestack, produced as many as 3000 Pb batteries per day following its construction in 1912 in the East Oakland flatlands until its closure in 1975 (EPA, 2011; Fimrite, 1996; Wesolowski et al., 1979). In 1918, the National Lead company constructed a Dutch Boy paint factory in the East Oakland flatlands that would remain operational for another half a century (DTSC, 2002, p. 2), providing paint for the city's houses and shipyards.

By the dawn of the Second World War, the soils of East Oakland, only a half-century earlier used for grazing and farming, were entirely covered with houses and buildings – most of them coated in lead paint. They were also crisscrossed with a grid system of roads from which TEL was emitted at a growing rate. The flatlands' endogenous soils had become entirely interspersed with, transformed into, or replaced with urbic or ekranic Technosols covered by infrastructure and constituted mostly of heterogeneous fill high in calcium carbonate, an artifact of building construction to which Pb has an affinity. The war opened up a flood of military capital that produced vast new swaths of land along the bay front, a massive expanse of spolic Technosols constructed from quarried rock and beach sand dredged from the estuary (Rogers and Figuers, 1991).[5] This new parent material not only provided the nascent soils with their structure and texture, but also their chemical make-up; high levels of metals and other contaminants were concentrated in fill dredged from the Estuary and the marsh flats of the East Bay due to decades of industrial effluent and pollution, landfill leachate, and urban stormwater runoff, as well as historical hydraulic mining sediment washed down Sacramento River during the Gold Rush (Hornberger et al., 1999; Hwang et al., 2009). This fill thus contributed to higher background Pb levels than endogenous soils further upslope. Together these Technosols, a hybrid of geomorphic processes and flows of capital, soon dominated Oakland's landscape, eventually totaling nearly 10,400 ha, or 75% of the city's area, primarily in the flatlands and foothills (NRCS, 2012).

Large-scale infrastructure projects facilitated the eastward expansion of residential and industrial capital across Oakland after the war. Highway construction and filling of wetland channels along the Alameda Estuary and San Francisco Bay shoreline moved massive volumes of soil across the city, new spolic and ekranic Technosols created to help maintain Oakland's role as backbone of the East Bay's industrial economy. An article in the California Highways and Public Works engineering bulletin sheds light on the scale of the disturbances that ultimately produced not only the major pathways from which TEL would be deposited, but also the soil chemical structure to which it would bind and the sandy texture that would facilitate speedier rates of chemical weathering: "300,000 cubic yards of saturated marshland mud and clay were excavated from the roadway site and placed to form dikes … 890,000 cubic yards of hydraulic fill are being pumped into the roadway section from a borrow area in San Francisco Bay" (Montell, 1948).

#### 3.3.3. Capital flows out

As UPE reminds us, urbanization is a socio-ecologically uneven process; capital accumulation somewhere means devaluation elsewhere. While industrial and residential capital fueled the eastward expansion of Oakland from the 1910s to the 1940s, racial covenants and "redlining" prevented this capital from flowing back westwards, resulting in the eventual devaluation of the flatlands – and consequent Pb contamination – that would disproportionately impact low-income people of color.

Land use controls such as these effectively quarantined people of color in the flatlands of North and West Oakland, Chinatown, and industrial areas along the Alameda Estuary. Originally drawn by the promise of jobs, new workers (many of them African Americans and immigrants) arrived by the thousands during World War I and the industrial boom that followed to work in the growing agglomeration of shipyards, warehouses, and factories along the estuary (Bagwell, 1982; Scott, 1985; Walker, 2001). The influx of workers was even greater during World War II. Racial covenants restricted home ownership in new subdivisions to whites. A Bright-Merrill Co. subdivision ad promised: "No saloons, no Japanese, Chinese, or negroes … beautiful views from the gentle foothill slopes … All these things spell sustained and rapidly increasing values" (*The San Francisco Call*, 1910, 15). Insurance agencies warned potential investors of "detrimental influences," notably the "infiltration" of "lower grades" such as "Negros," "Orientals," and "lower classes" (HOLC, 1937), ranking most African–American neighborhoods as "hazardous" and color-coding them red on the maps (see Fig. 6). White neighborhoods, on the other hand, received higher ratings if they had racial covenants in place. Homes in redlined areas rarely qualified for loans and became increasingly dilapidated, their paint flaking away and adding new species of Pb to the flatlands soil.

Post-World War II suburbanization driven by industrial relocation and federally subsidized residential development transformed the East Bay. But unlike the city's pre-war expansion eastwards, Oakland did not prosper this time around. The new highways ultimately facilitated the development of the rural bayside land between Oakland and San Jose, and the marshy shoreline rapidly morphed into a chain of industrial suburbs – San Leandro, Hayward, Fremont, Union City, Newark – that drained Oakland of industrial capital, a solid tax base, and much of its white population (Self, 2003; Walker, 2001). More than 130 factories in Oakland shut their doors in the three decades following the end of the war, and the city's share of the county's manufacturing capital dropped from half to a third as production shifted to the new factories (see Table 6). Nearly 10,000 manufacturing jobs were lost by 1977, leading to skyrocketing unemployment; Oakland's

[5] A more expansive CPG might relate these and earlier inflows of military cital to the political economy of US expansionism in the Pacific and the critical role that military capital – and associated R&D at the region's universities – played in the urbanization of the San Francisco Bay Area (Brechin, 2006; Johnson, 1993).

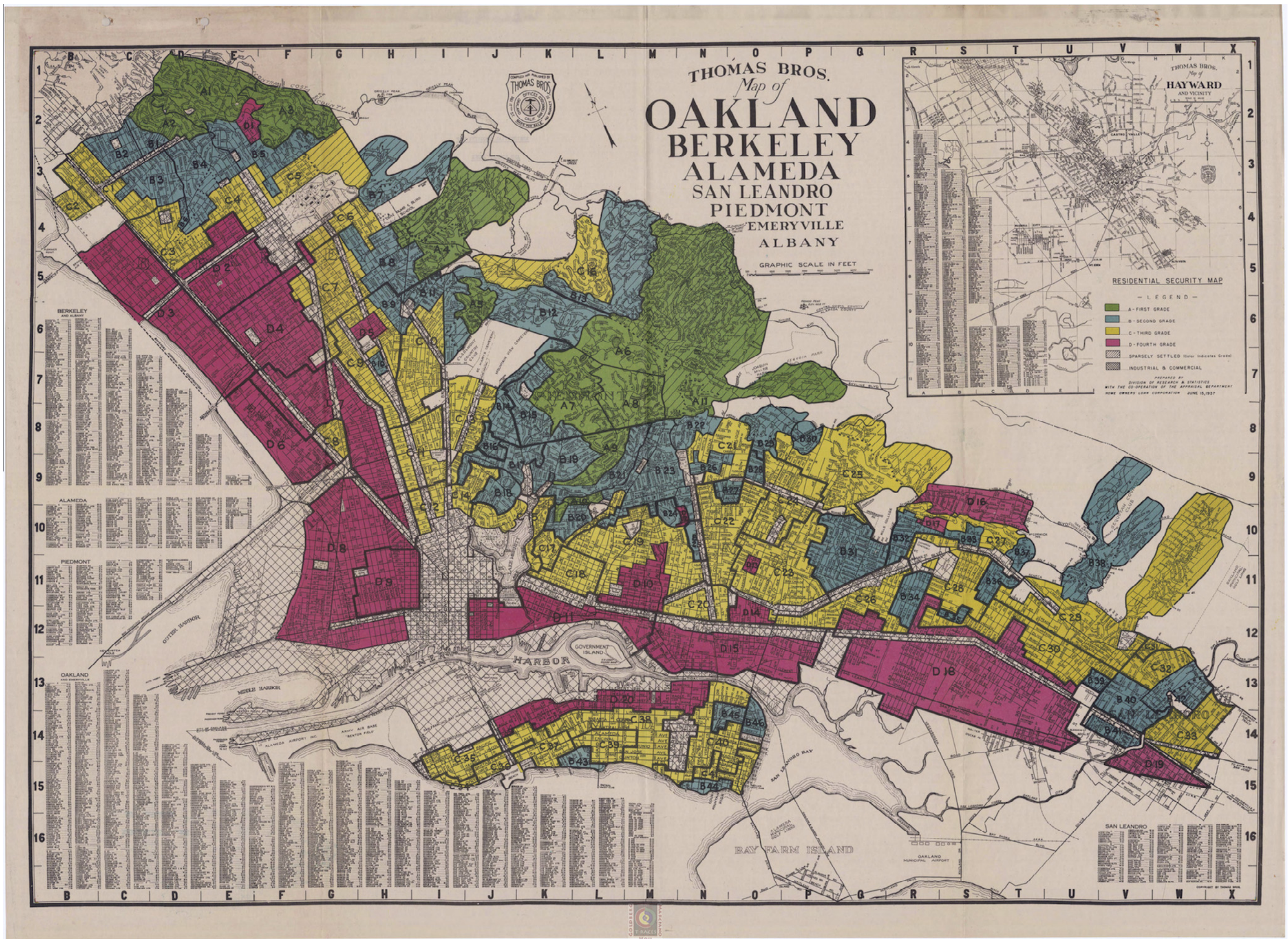


**Fig. 6.** A 1937 "redlining" map of Oakland, published by the Homeowner's Loan Corporation. Areas colored red (primarily in West Oakland and along the estuary) were ranked as D-Grade, or high risk, due to the presence of African Americans and other minority groups. Such a rating prevented mortgage lending and other forms of investment. *Source:* HOLC (1937).

**Table 6**
Decline of manufacturing in Oakland and increase in Alameda County, California, 1939–1987. *Data source:* US Census Bureau (1947, 1958, 1967, 1977, 1987).

| Year | Manufacturers | | Workers | | Value added by manufacturing | |
|---|---|---|---|---|---|---|
| | Oakland | Rest of Alameda Co.[a] | Total | Rest of Alameda Co.[a] | $ (millions) | Share of Alameda Co. total (%) |
| 1939 | 549 | 344 | 15,935 | 10,911 | 67.7 | 55 |
| 1947 | 701 | 485 | 25,601 | 28,437 | 207.6 | 51 |
| 1958 | 824 | 727 | 24,305 | 25,751 | 377.1 | 47 |
| 1967 | 748 | 956 | 19,100 | 36,200 | 417.1 | 32 |
| 1977 | 692 | 1365 | 16,300 | 42,200 | 739.1 | 34 |
| 1987 | 717 | 1735 | 11,800 | 35,500 | 1095.7 | 16 |

[a] Calculated by subtracting Oakland data from Alameda Co. data.

unemployment rate in 1964 was 11%, but for African–Americans was almost twice that high.

Industrial relocation allowed for the physical expansion of firms, and privileged white workers. Working-class whites moved to the suburbs, following the jobs and the promise of home ownership in the new racially restricted housing developments (Self, 2003; Walker, 2001). This process fundamentally redefined the social landscape of the flatlands. While the Oakland hills continued to house Oakland's white elite, the flight of the white working class to the suburbs opened up the East Oakland flatlands to people of color for the first time. Redlining prevented (or dissuaded) any investment in new construction or repairs there, however. Even after redlining was prohibited under the 1968 Fair Housing Act, it continued in a self-reproducing, de facto manner due to housing prices and the spatialized legacy of denied loan applications (Kantor and Nyusten, 1982). Housing in the East Oakland flatlands – more than two-thirds much of it owned by absentee landlords by the late 1970s (Henze et al., 1979) – became dilapidated as it had in West Oakland decades earlier, a social process imprinted in the soil memory in the form of Pb oxides and hydrocerrusite, impacting a human population that was becoming less white and less affluent.

In addition to facilitating the rapid suburbanization the East Bay, the construction of major transportation corridors served as an important source of Pb deposition while helping to materially reinforce socio-spatial divisions in Oakland, physically demarcating what zoning and redlining did on paper. Freeways were sited in devalued flatlands neighborhoods where land values were low and the political power of the predominantly non-white population marginal. The Grove Shafter Freeway was placed along the redline that separated West Oakland from downtown, the MacArthur Freeway divided the flatlands from the hills, and the East Shore Freeway was sited through the city's low-income industrial corridor along the shoreline of the Alameda Estuary and San

Leandro Bay. The Cypress Freeway was constructed through the middle of West Oakland, razing hundreds of homes and displacing thousands of African American residents (Self, 2003). Residential property values dropped further as traffic increased, air quality deteriorated, and Pb deposition increased, fueling the cycle of devaluation (O'Connor, 1998, p. 297).[6]

The demarcated devaluation of the flatlands was thus, in effect, a socio-ecological process. A CPG shows us how the social landscape and the properties of its soils are intimately linked to this spatial history of uneven flows of capital in and out of the flatlands during the first half of the twentieth century. Like the urban landscape of prosperity that developed during Oakland's industrial boom years, the racialized neglect that followed in the wake of redlining, deindustrialization, and tax revolts mediated the spatiality of Pb deposition from housing stock and automobile exhaust. The high proportion of rentals exacerbated the poor state of the housing stock that has been persistent source of Pb additions to the soil as old paint flakes away. Freeways depositing Pb and other contaminants demarcated these dilapidated flatlands neighborhoods. This highly spatialized process left a material legacy, recorded in the soil palimpsest and bone tissue alike, socio-natural hybrids still present and active decades after a vehicle last burned TEL and a house received its last coat of Dutch Boy white lead paint.

## 4. Conclusion: Toward a material politics of place

Since soils are "polygenetic" (Richter and Yaalon, 2012), deciphering their multiple genealogies requires acute attention to various processes unfolding at different temporal and spatial scales. This brief CPG of soil Pb in Oakland illustrates the co-production of social relations and soil processes across time and space. Urban soil Pb's multiple forms are, to a certain extent, predetermined by the chemical requirements of stoichiometric equilibrium and weathering sequences. But they are also hybrids because they are contingent upon a suite of socio-historical, pedogenetic, and climatic factors mediating soil disturbance. Instead of simply tracing the deposition of a contaminant to a particular source or mechanism, a CPG helps us to uncover the historical political economic forces and power relations that led to a particular land use in a particular place and time, to witness the influence of differential metabolism on biogeochemical processes, and to demonstrate how the socio-natural hybrids that resulted from these processes were transformative in their own right, both emerging from and contributing to the socio-spatial devaluation of the built environment and the lives of those inhabiting it.[7]

At the same time, and perhaps even more importantly for political action, such an analysis can help to situate present-day environmental injustices within longer historical contexts of structural racism and the demarcated devaluation of the Oakland flatlands or similar places, while recognizing the import of non-human processes, which is crucial, given that "the future effects of contamination will also be contingent on myriad processes involving microbes, vegetation, microclimates, and mineral weathering" (Engel-Di Mauro, 2014, p. 175). Attention to the materiality of soil Pb can contribute to a "situated strategy" or "politics of location … both metaphysical and concrete. Matter matters because it is through grounded research that we encounter difference that makes a difference" (Bakker and Bridge, 2006, p. 21). But matter also matters because "the properties of the material world can be remarkably durable" (Bakker and Bridge, 2006, p. 14), while the social construction of the material world is historically and geographically contingent. Certain forms of Pb are and will always be toxic, whereas how we understand Pb and how we use it, has changed—thanks to scientific study, the "everyday environmentalisms" (Loftus, 2012) of lived experience, and political struggle.

Throughout the twentieth century, and especially since the late 1980s, East Bay residents, often recruiting the help of local environmental non-profits, successfully fought polluters in the streets and courtrooms over the state of the soil and sky, demanding protection for the health of the area's residents (Walker, 2007). Activists, united with organizations such as Urban Habitat, began to employ a "flatlands framework" to illuminate the inequities between the affluent white populations living in the East Bay hills, on the one hand, surrounded by a network of regional parks and views of the Bay, and the low-income populations living below in concrete flatlands, on the other, surrounded by toxic soil, water, and air. This "spatial justice agenda essentially fill[ed] in for a racial (or, more appropriately, multiracial) agenda" (Pastor et al., 2009, p. 69) – of low-income blacks, Asians, and Latinos – which likely would have been threatening to whites. By framing their struggles spatially, EJ and social justice activists have been able to consolidate struggles about poverty, race, health, and environment into a unifying theory of place that has been perhaps more tenable for white liberal environmentalists, municipal planners, and public health officials. Engaging in a "flatlands politics" (O'Connor, 1998, pp. 295–298) – rather than holding fast to the "militant particularism" (Harvey, 2001; Williams, 1980) of a struggle over an individual contaminated site – has therefore allowed EJ activists to invoke historicized structural understandings of the broader urban environment while pushing for various clean up efforts throughout the city.

The EPA's Fishbone Project, where I began this paper and will end, is only the latest example of such a material politics of place that a CPG can help us understand. In this instance, community activists invoked a history of spatialized inequity and the double burden of poverty and contamination to demand that the proposed remediation include jobs and training for low-income community members. They also pressed for the new bioremediation technique over conventional soil removal and disposal, which they saw as simply passing their problem along to some other low-income community (S. Calanog, personal communication). Instead, neighborhood residents were trained as technicians who then tilled ground-up pollock (*Pollachius* spp.) bones, a waste product of the Alaskan fishing industry, into West Oakland's soils. This new garbic parent material thus entered the pedosphere, joining a complex of urbic Technosols and the endogenous Baywood sandy loam, bonding with more weakly bound soil Pb to create a new Pb species: pyromorphite. A CPG allows us to recognize this new mineral as a socio-natural hybrid whose very materiality – Pb in its most recalcitrant form – embodies in its lattices not only the minerals weathered from Pleistocene alluvium and Quaternary sand, TEL combusted in the mid-20th century, and phosphorus and calcium from the bones of fish caught off of Alaskan waters, but also the flows of capital and the politics of resistance that mediated their coming together in time and space, a new hybrid socio-natural matter that matters.

[6] The demarcated devaluation of the flatlands was exacerbated by a conservative tax revolt led by a class alliance of developers and conservative white homeowners in the new suburbs. Proposition 14, a 1964 ballot initiative sponsored the California Real Estate Association, essentially overturned the federal Fair Housing Act, passed the year before. In 1978 this same alliance was able to pass the infamous Proposition 13, which severely limited cities' ability to raise property taxes. The resulting decrease in property taxes took a toll on Oakland's already impoverished flatlands, as inflow of revenue was squeezed by more than $14 million (or roughly $50 million in 2013 dollars), leading to facilities closures and cuts to public services (Rhomberg, 2004; Self, 2003; Simon, 2014; Walker and Schafran, 2015).

[7] I think this holds true even where relationships of race and class are less tied to a historical and political economic context of home ownership and racial segregation than that which is described here. Clearly, the processes and outcomes will surely differ, given historical and geographic contingency, but as UPE scholars have demonstrated over the past decade, analytical attention to social metabolism – and to the materiality of the hybrid socio-natures that emerge – can be insightful in a diversity of geographic contexts.

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## Appendix A. Field, lab, and geospatial methods

The study context and sampling protocol are described in detail elsewhere (McClintock, 2012; McClintock et al., 2013). Briefly, I randomly selected twenty sites in each of Oakland's seven City Council Districts using ArcGIS. A Moran's I test of spatial autocorrelation confirmed that sites were randomly distributed across the city. My research assistants and I then collected composite samples from 113 sites across the city (the remaining sites excluded due to inaccessibility). Each sample comprised twelve georeferenced soil cores collected at a depth of 5–10 cm. The UC Davis Analytical Lab analyzed all samples for total Pb using Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) after a nitric acid/hydrogen peroxide closed vessel microwave digestion (Sah and Miller, 1992). We analyzed all samples for pH, total carbon (C) and nitrogen (N) at UC Berkeley following EPA protocols (EPA, 2007).

To assess correlations between anthropogenic influences on soil Pb levels, I used Pb data from all 113 sites. To assess the influence of selected soil chemical properties, I purposively selected a geographically representative sub-sample ($n = 50$; see Supplementary Geospatial Data). These samples were further analyzed at UC Davis for total phosphorus (P) and calcium (Ca). A&L Western Labs provided soil texture data. The physico-chemical characteristics of these soils are reported in Table 2.

I used ArcGIS for mapping, GeoDa for spatial statistics, and JMP to conduct ordinary least squares (OLS) regression, distribution tests (Shapiro–Wilk W, Kolmogorov's D), and Pearson's correlations. Distribution of total Pb data of the sub-sample was similar to that of the overall data set: highly skewed (skewness = 6.454, kurtosis = 50.452) and lognormal with lognormal distribution. I therefore log-transformed total Pb, total P, and total Ca data to meet assumptions of normality for regression.

To identify anthropogenic sources associated with Pb deposition, I used a stepwise OLS model to test the effect of several anthropogenic factors on total soil Pb. Based on a review of the literature on sources of Pb contamination (see Section 2.1), I initially included the following variables of interest: land use (garden, open space, park, and vacant; see McClintock, 2012) and zoning type (residential, industrial, and open space); distance to major roads, industrial sites, and airport (see Fig. 2) as measures of proximity to sources of airborne Pb contamination; and the density of pre-1940s housing stock as a proxy for aged housing stock and paint-based contamination. I conducted Pearson's correlation to identify relationships between Pb and other soil chemical factors known to complex with Pb – Ca, P, and C – and pH, which mediates its solubility and the weathering of Pb-complexes.

After testing for multicollinearity by comparing variance inflation factors (VIF) and removing variables with VIF > 2 (e.g. percent renter-occupied, median household income), I developed an OLS model that included both anthropogenic and soil physicochemical factors. Given that the local point pattern analyses revealed slight spatial autocorrelation of Pb levels (McClintock, 2012), I included a spatial lag term in the OLS model, having used Ripley's K analysis to generate the appropriate spatial weight. The addition of a spatial lag term slightly improved the coefficient of determination ($R^2$) and Akaike information criterion (AIC) of the model, both measures of the model strength. After stepwise regression to exclude non-significant variables ($p > 0.10$), the final model included six independent variables. Three anthropogenic variables included in the model were: distance to major roads, block group density of pre-1940s housing, and block group percentage of renter-owned housing. Three geochemical variables were: C/N ratio, log P, and log Ca. Finally, I tested residuals for spatial autocorrelation using Moran's I to verify that the model was appropriate.

## Appendix B. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.geoforum.2015.07.010. These data include Google maps of the most important areas described in this article.

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