able to return to its original shape after being deformed. P-waves and S-waves travel through the solid interior of the Earth. In addition, surface waves of several types travel along the surface of the Earth; these waves produce most of the damage in earthquakes (Richter, 1958).

The power of earthquakes is measured in two ways. Intensity, usually measured on the 12-point Mercalli scale, is a measure of the shaking observed at some particular location. Intensity varies from place to place. Magnitude is determined from seismic records and is measured on the *Richter scale* (Richter, 1935). This is now known as the *local magnitude scale* and has largely been replaced by the *moment magnitude scale*, which is more accurate in the higher ranges. Magnitude is a measure of the energy released by the earthquake. Each increase of one unit on the Richter scale corresponds to an increase of approximately 30 times in energy. The Richter scale has no upper limit, but very tiny earthquakes are seldom studied because there are too many other sources of faint vibration in the Earth, like storms or human-made noise. At the upper end of the scale, the Earth's crust simply cannot store more strain energy than needed to produce earthquakes of about moment magnitude 9–10.

Studies of seismic waves have allowed seismologists to map the inner structure of the Earth and determine that the Earth consists of a thin crust, a thick solid mantle, and a core a bit more than half the diameter of the Earth (Anderson and Dziewonski, 1984). The core consists of two parts. The outer core is liquid, as shown by the fact that it does not transmit S-waves. The inner core, about half the diameter of the core, is solid.

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Cross-references

Disaster
Earthquakes, Damage and its Mitigation
Earthquake Prediction
Geologic Hazards
Natural Hazards
Risk Assessment
Seismology, Seismic Activity

SELENIUM POLLUTION

Selenium is an essential dietary micro-nutrient with the narrowest range between where essentiality ends and toxicity begins (US NAS, 1980). Natural selenium pollution studies began in the 1940s, prompted by the poisoning of livestock in the western United States (Trelease and Beath, 1949). This 'alkali disease' was traced to elevated amounts of selenium in 'accumulator plants' of the genus *Astragalus* growing on salinized soils. These soils are mainly derived from marine sedimentary rocks of Cretaceous age that crop out over approximately 830,000 km^2 of the western United States. These rocks include the Pierre and Niobrara Shales which have the highest selenium concentrations.

Having similar chemical properties, selenium and sulfur are found weathered together, reflecting a possible original association. In theory, large quantities of selenium were introduced into the oceans and accumulated in sediment as a result of major volcanic activity during the Cretaceous Period (Trelease and Beath, 1949). From natural abundances, sedimentary rocks contain more selenium (shales 0.6 ppm) than do igneous rocks (0.05 ppm) (Adriano, 1986). During certain geologic processes, including diagenesis of marine sediments, selenium is thought to be preserved because of its ability to substitute for sulfur in mineral lattices (Coleman and Delevaux, 1957). Most selenium is found in sulfur-bearing minerals, with shales containing pyrite (FeS_2), the most widespread and abundant sulfide mineral, being reported with up to 300 µg/g selenium. When uplifted, exposed, and weathered, these shales can be an important source of selenium released into the environment.

Selenium may occur as selenide ($Se^{=}$), elemental selenium (Se^{0}), selenite ($SeO_3^{=}$), or selenate ($SeO_4^{=}$) (US NAS, 1976). Little transport of selenium takes place either under reducing conditions, where insoluble elemental selenium and metallic selenides exist, or under acidic-oxidizing conditions, where selenite occurs as stable iron and aluminum complexes. It is only under alkaline-oxidizing conditions that selenium is most soluble as selenate.

Three processes are important in defining the toxicity of selenium in the natural environment: mobilization, enrichment, and consequent establishment of selenium-containing biological compounds.

Two scenarios have been identified for mobilization. First, weathering and erosion of marine sedimentary rocks provide a renewable source of selenium, which may be ultimately mobilized as soluble selenate if derived soils form under oxidizing alkaline conditions (Presser and Swain, 1990). Contaminated areas contain characteristic soluble sulfate salts in which selenate (SeO_4) may substitute for sulfate (SO_4) in the mineral lattice. Soil salinization may occur due to evapotranspiration of shallow groundwater in arid areas causing excessive accumulation of sulfate and selenate salts. Remediation of salinization detrimental to crop productivity has led to the installation of subsurface drains 2.5–3 m below land surfaces to carry away excess water and soluble salts after irrigation. Collection and disposal of these soil leachates have created a new type of environmental pollution, subsurface drainage (Presser *et al.*, 1994). Classified as agricultural return flows, these waste waters are exempt from the US Clean Water Act (US EPA, 1987). Selenium concentrations exceeding the criterion for designating the leachate as a toxic waste (1000 µg/liter) have been identified in drains in the western San Joaquin Valley, California (Presser and Ohlendorf, 1987). Current management allows its use to support wildlife habitat in wetland areas that also act as evaporation systems. This use decreases water volumes but concentrates potentially toxic trace elements.

Secondly, the mobilization of selenium from the combustion of seleniferous coal (2–20 µg/g) generates a fly ash that contains even higher levels of oxidized, water-soluble selenium (50–500 µg/g) that can be leached away and carried into nearby cooling water reservoirs, lakes and streams in the course of its disposal (Lemly, 1985).

Enrichment occurs through the introduction of selenium-bearing water into wetland environments where bacteria and plant growth is favored (Lemly, 1985; Presser and Ohlendorf, 1987). Here selenium enters the food chain, so that increased selenium levels are found progressively up through higher organisms (see entry on *Bioaccumulation, Bioconcentration, Biomagnification*). This results in dietary levels for birds and fish that are associated with reproductive failure and teratogenic deformities in the laboratory (Ohlendorf, 1989). Instances of known reproductive effects among wildlife due to selenium levels were first identified in 1977 at Belews Lake in North Carolina for fish (Cumbie and Van Horn, 1978) and in 1983 at Kesterson National Wildlife Refuge in California for birds (Ohlendorf *et al.*, 1986). Extremely low concentrations of selenium in the water column of wetlands (2.3 μg/liter) have been confirmed for initiation of toxicity in the bird and fish communities (Skorupa and Ohlendorf, 1991).

Bioaccumulation (*q.v.*) is postulated to be caused by selenium substituting for sulfur in the sulfur-containing amino acids cysteine and methionine (Stadtman, 1974), thus establishing selenium-containing biological compounds in the environment. Biomagnification occurs when simple organisms,(e.g., bacteria, algae, fungi and plants), which are able to synthesize essential amino acids *de novo*, are consumed by progressively more complex species as their source of amino acid building blocks, thereby resulting in accumulation of amino acids that contain selenium. Inability to discriminate between selenium and sulfur leads to altered structural and functional proteins including immunoglobulins. This, in turn, could lead to the generation of multiple congenital anomalies, sterility and suppression of the immune system if elevated selenium concentrations are present in an organism at critical development stages when rapid cell production and morphogenic movement are occurring (Figure S10; Presser and Ohlendorf, 1987).

With Kesterson as a prototype, similar irrigation–drainage sites in the western United States have been identified in which selenium levels have been associated with reproductive failure in birds (Presser *et al.*, 1994). An analogy can be drawn between selenium accumulation in present-day pond ecosystems and in the ancient, shallow, marine areas of nutrient-rich continental shelf and slope environments. It is hypothesized that these latter environments were major sinks for selenium in ancient oceans, and the consequent geologic formations deposited there are now major sources of selenium. This is exemplified in the formations of the central California Coast Ranges, the source area for selenium adjacent to the Kesterson National Wildlife Refuge (Presser, 1994). Similar coal fly-ash disposal sites where reproductive failure in fish is associated with increased selenium levels have been identified at locations in North Carolina and in Texas; a summary of teratogenic effects in fish is given in Lemly (1993).

The Kesterson National Wildlife Refuge site was declared a toxic waste dump and buried in 1986 due to accumulated

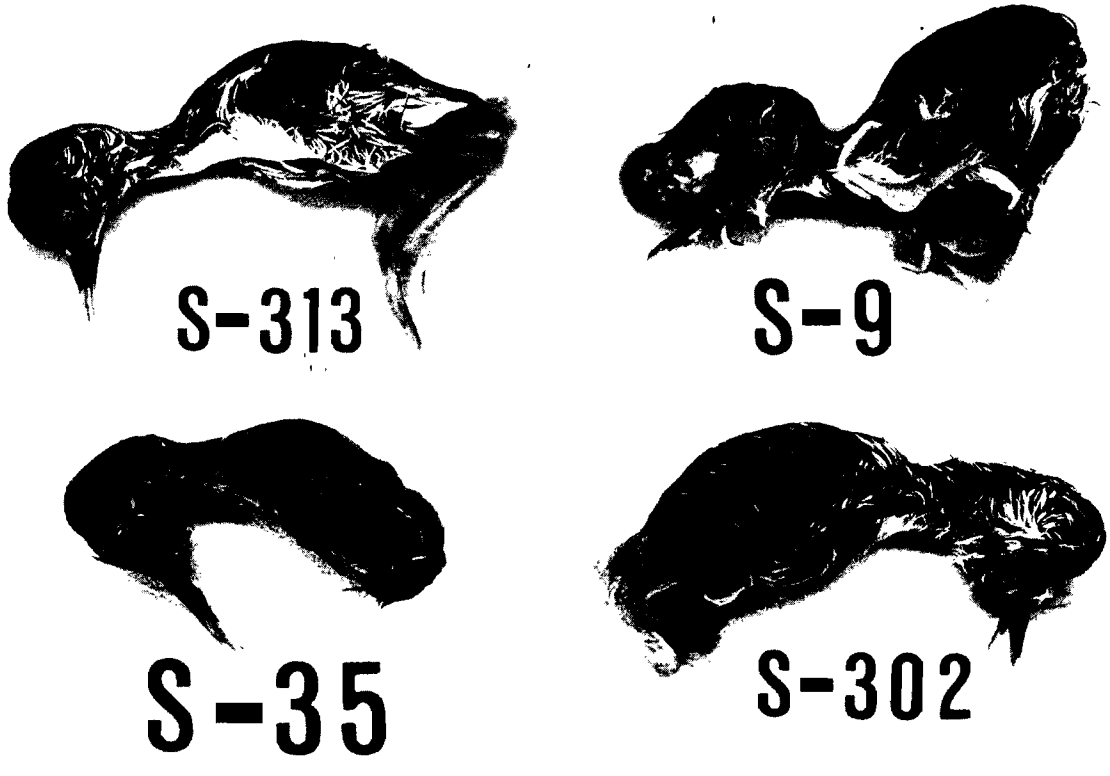

Figure S10 Black-necked stilt embryos from nests at Kesterson Reservoir. **S-9**: eyes missing, severe exencephaly through orbits, lower beak curled, upper parts of legs shortened and twisted, and only one toe on each foot. **S-35**: eyes missing, encephalocele, upper beak elongated and eroded at nostrils, lower beak missing, legs missing, and only one (small) wing. **S-302**: eyes missing, upper beak curved, lower beak shortened and tip of lower beak hooked, hydrocephaly, edema in throat, legs twisted and feet shortened with only one toe on each foot. **S-313**: normal (Reprinted from Presser and Ohlendorf, 1987, with permission from Springer-Verlag, New York, Inc.).

selenium. Contamination of the terrestrial food chain has subsequently occurred at this site because of remobilization of selenium (USBR, 1993). In view of the seriousness of selenium biogeochemical cycling (see entry on *Cycles, Geochemical*), exposure potential, including local food market surveys, may be necessary to assess selenium criteria levels since the concentration of selenium in water is not always reflective of the amount of uptake in the food chain (Presser *et al.*, 1994).

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Cross-references

Arsenic Pollution and Toxicity
Cadmium Pollution and Toxicity
Environmental Toxicology
Health Hazards, Environmental
Heavy Metal Pollutants
Lead Poisoning
Mercury in the Environment
Metal Toxicity

SEMI-ARID CLIMATES AND TERRAIN

Semi-arid climates

Differences in the prevailing land use and management of arid and semi-arid areas are determined in part by climate. Arid areas generally receive too little rainfall to support dryland agricultural or domestic livestock grazing. In contrast, in semi-arid areas adequate moisture is usually available at some time during the year to produce forage for livestock, and there are some years when dryland crop production is successful (Heath *et al.*, 1985; Penman, 1963). However, both climates are characterized by extreme variability, with commonly occurring droughts and infrequent periods of above-average rainfall.

Most arid areas of the world occur along two wide belts at approximately 30° latitude north and south of the equator (Lydolph, 1985). In these subtropical belts, the winds generally descend and are dry much of the time. Semi-arid areas associated with the arid deserts generally occur north and/or south of the deserts (in Africa, Asia and Australia) or inland and at slightly higher elevations (in North America, South America, the Middle East, Africa and Asia). On a more localized scale, a combination of terrain and prevailing wind direction can cause 'rain shadow' effects, resulting in arid and semi-arid areas downwind of major mountain features (Oliver and Fairbridge, 1987).

More than a third of the world's land surface is either arid, generally receiving less than 250 mm of annual precipitation, or semi-arid with between 250 mm and 500 mm of annual precipitation. More precise definitions of desert and semi-arid areas are given in climatic classifications based on precipitation, temperature and their seasonal distributions. For example, following Trewartha and Horn (1980), and based on extensive classifications of Köppen (1931), upper and lower mean annual precipitation limits defining semi-arid climates are as follows.

Semi-arid climates, for regions where annual precipitation is not strongly seasonal, are defined by equations linking mean annual values of precipitation, R, in mm, and temperature, T, in degrees C. The upper limit for semi-arid climates, in terms of mean annual precipitation given a specific value of mean annual temperature, is defined by

$$R \leq 20T + 140$$

The corresponding lower limit that separates arid and semi-arid (or alternatively desert and steppe) is defined as half the value of the upper limit from the above equation, or

$$R \geq 10T + 70$$

Temperature and precipitation data from selected locations in arid and semi-arid areas of the world were used to classify climate based on the above criteria and a designation for hot (*h*, with 8 or more months of the year with average temperature above 10°C) and cold (*k*, with fewer than 8 months of the year with average temperature above 10°C). The general classification for dry climates is *B* and the specific classification for semi-arid is *S*. Thus, *BSk* represents a cold semi-arid climate and *BSh* is a hot semi-arid climate. These classifications and