

Transoceanic Transport Mechanisms: Introduction of the Chinese Mitten Crab, *Eriocheir sinensis*, to California¹

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ABSTRACT: Live importation of the Chinese mitten crab, (*Eriocheir sinensis* H. Milne-Edwards, 1854) was banned by both California and the United States in the late 1980s because of concerns about potential damage to levees, rice crops, and natural ecosystems, and because it harbors a human parasite. Nevertheless, mitten crabs were present in San Francisco Bay by 1992 and well established by 1994, providing the most recent example in a late-twentieth-century pulse of human-mediated transoceanic and interoceanic crab dispersals. Of 10 mechanisms available for the long-distance transport of crabs, evidence from the history of the mitten crab's global spread, data on ship traffic, the sampling of ballast water fauna, and recent patterns of introductions support the hypothesis of introduction via ballast water. Alternatively, the pattern of governmental interception of mitten crabs, their high market value, and continuing pressure to lift the import ban suggest that introduction may have been achieved via an intentional, private-party inoculation to establish a food resource. For either mechanism, the immediate source is more likely Asia than Europe. Amid a global burgeoning of potential transport mechanisms for estuarine and neritic organisms, knowledge of which mechanisms are in fact acting is essential for directing efforts to moderate the pace of such introductions.

IN THE LAST THIRD of the twentieth century, there have been numerous reports of the transport and introduction of brachyuran crabs to various parts of the globe. The northwestern Atlantic brackish-water mudcrab, *Rhithropanopeus harrisi* (Gould) (Xanthidae), and the Indo-Pacific crab *Elamenessis kempfi* (Chopra & Das) (Hymenopomatidae) were collected from the Panama Canal in 1969 (Abele 1972, Carlton 1979). The eastern Pacific spider crab, *Pyromaia tuberculata* (Lockington) (Inachidae), appeared in Japan in 1970 (Sakai 1976a) and near Auckland, New Zealand, in 1978 (Webber and Wear 1981). The western Atlantic blue crab, *Callinectes sapidus* Rathbun (Portunidae), has been reported from Japan since 1975 and in Hawai'i since 1985 (Eldredge 1995). A specimen of the northeastern Pacific Dungeness crab, *Cancer magister* Dana (Canceridae), was collected in Japan in 1979 (Abe 1981). The European green crab, *Carcinus mae-*

nas (L.) (Portunidae), introduced to northwestern Atlantic and southern Australian waters in the nineteenth century, was first collected in South Africa in 1983 and in California in 1989-1990, and is now established in both regions (Le Roux et al. 1990, Cohen et al. 1995). The Indo-Pacific crab *Charybdis helleri* (A. Milne-Edwards) (Portunidae) was collected in both the southern and northern Caribbean in 1987-1988 and in Florida in 1995 (Campos and Turkey 1989, Gómez and Martínez-Iglesias 1990, Lemaitre 1996). The Japanese shorecrab *Hemigrapsus sanguineus* (de Haan) (Grapsidae) became established in the eastern United States by 1988 (McDermott 1991).

Brachyuran crabs frequently are habitat generalists, and with the rapidly expanding volume and variety of international trade, travel, and maritime activities, multiple possible mechanisms of transoceanic and interoceanic transport have become available to them. Understanding which mechanisms are actually operating to transport these organisms is essential to developing effective control strategies.

We report here on the establishment of the

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Chinese mitten crab, *Eriocheir sinensis* H. Milne-Edwards, 1854, in San Francisco Bay, California, and analyze the suite of possible mechanisms that could have transported it to California.

MATERIALS AND METHODS

To determine the status of *E. sinensis* in the eastern Pacific, we circulated a Mitten Crab Wanted poster to and interviewed regional biologists, commercial shrimpers and bait trappers, and personnel at bait stores and marinas for possible records and specimens. All specimens were examined for epizoids and their carapace length measured. We compared San Francisco Bay specimens with *E. sinensis* specimens obtained from Germany and with Japanese specimens at the California Academy of Sciences.

We searched the global invasion literature for mechanisms of long-distance transport applicable to brachyuran crabs, which we compared with the circumstances pertaining to the arrival of *E. sinensis* in California, including relevant aspects of its biology and life history. Based on this initial review, the likeliest mechanisms were further investigated by (1) reviewing shipping and ballast water records, and (2) interviewing wildlife inspectors.

RESULTS

Establishment in the Northeastern Pacific

In November 1994 *E. sinensis* was identified from San Francisco Bay by Robert Van Syoc of the California Academy of Sciences. Commercial shrimp trawlers (listed in the Acknowledgments) reported catching such crabs occasionally, many with eggs, since 1992 in southern San Francisco Bay and since the summer of 1994 in northern San Francisco Bay (San Pablo Bay) (Figure 1). Of 75 mitten crabs examined that were collected in San Francisco Bay between winter 1993 and spring 1995, 52 were male, 32–76 mm in carapace length; 18 were ovigerous females, 35–70 mm in length; and five were nonovigerous females, 43–55 mm in length. Most of these were taken in shrimp nets trawled along channel bottoms at 6–15 m depth.

Crabs entangled in fishing line or collected by park personnel were taken at the mouth of the Petaluma River in northwestern San Pablo Bay, at the Dumbarton Pier in the South Bay, and on the Hayward shore. In September 1995 we found smaller crabs in the drying bed of the Alameda Flood Control Channel at 9 and 12 km upstream from the bay, concentrated in small pools and in shallow burrows in damp mud under rocks, where we collected 54 crabs, 12–36 mm in length, in a 10-min search, along with the introduced crayfish *Procambarus clarkii* (Girard) (two specimens) and *Pacifastacus leniusculus* (Dana) (one specimen); in July 1996 the remains of several crabs were found in the channel 15 km from the bay. Thousands of young crabs and burrows have now been observed (1995–1996) in tidal creeks at the southern end of San Francisco Bay (K. Halat, pers. comm., 1996); two crabs, ca. 35 and 60 mm in carapace width, were collected in Suisun Marsh sloughs in February and May 1996 (S. Matern, pers. comm., 1996); and in May 1996 we observed a few crabs, 4–5 mm in length, among tubes of the introduced serpulid worm *Ficopomatus enigmaticus* (Fauvel) fouling docks in the Petaluma River in Petaluma, 20 km northwest of San Pablo Bay. In September 1996, adult mitten crabs were collected at several sites in the fresh waters of the Sacramento-San Joaquin Delta, upstream of the Bay in California's Central Valley.

Several female *E. sinensis* collected from southern San Francisco Bay in the winter of 1994–1995 were maintained in aquaria by the Marine Science Institute of Redwood City, California, and hatched active zoeae by the first week of February 1995. The number of crabs present, their persistence over several years, their broad distribution within the bay and its tributaries, and the presence of a range of size classes and of females carrying eggs and hatching larvae all indicate that the mitten crab is well established in San Francisco Bay; the lack of any prior records of this distinctive crab strongly suggests that it could not have been introduced much earlier than about 1990.

The crabs examined were generally free of epizoids; those found were the barnacle *Balanus improvisus* Darwin, the seaweed *Ulva* sp., egg cases of the snail *Ilyanassa obsoleta* (Say), and small stalks of a hydroid, cf. *Garveia franciscana* (Torrey), with an epizoid entoproct *Barentsia benedeni* (Foettinger) and ciliate *Zoothamnium* sp. All of

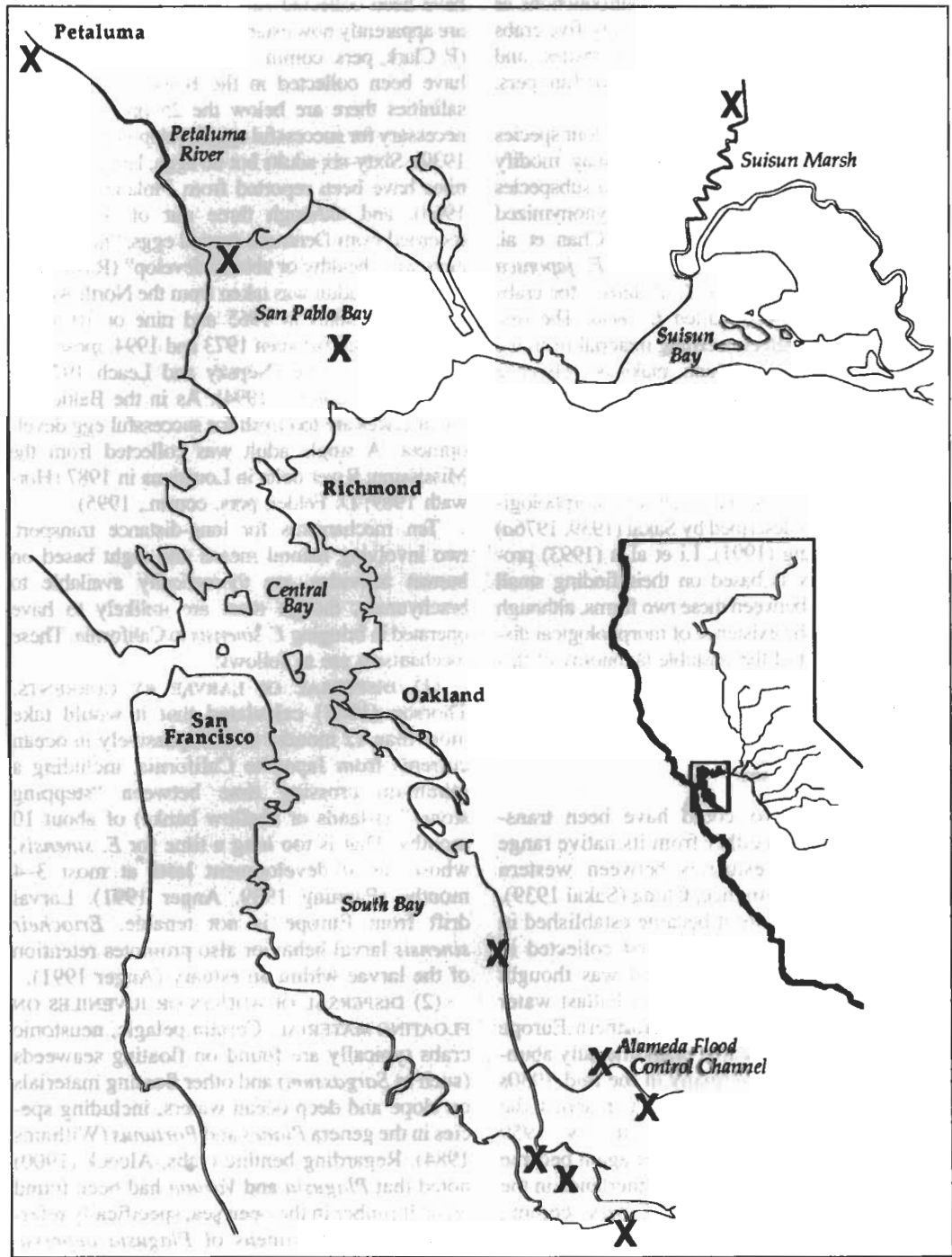


FIGURE 1. *Eriocheir sinensis* in San Francisco Bay, California. Sites at which *E. sinensis* were collected are marked by an "X."

these taxa are known or probable introductions as well (Cohen and Carlton 1995). Twenty-five crabs were dissected and examined for parasites, and none were found (A. Kuris and M. Torchin, pers. comm., 1995).

Workers have generally recognized four species of *Eriocheir*, although recent work may modify this arrangement. Dai (1993) created a subspecies under *E. japonica*, Li et al. (1993) synonymized *E. sinensis* under *E. japonica*, and Chan et al. (1995) synonymized *E. recta* under *E. japonica* and created a new species, *E. formosa*, for crabs from Taiwan that were called *E. recta*. The first two papers, although concerning material from the same area in southern China, make no reference to each other, whereas the third describes the conclusions of the earlier two as "premature." Specimens of *E. sinensis* (from Germany) and *E. japonica* (from Japan) that we have examined are distinguished by clear and consistent morphological differences as described by Sakai (1939, 1976a) and Dai and Yang (1991). Li et al.'s (1993) proposed synonymy is based on their finding small genetic distance between these two forms, although they confirmed the existence of morphological distinctions. In light of the unstable taxonomy of this genus, we continue to treat *E. sinensis* as a species distinct from *E. japonica*.

Transport Mechanisms

Eriocheir sinensis could have been transported to California either from its native range in the rivers and estuaries between western Korea and Fujian Province, China (Sakai 1939), or from Europe, where it became established in the twentieth century. It was first collected in Europe in Germany in 1912 and was thought to have been transported there in ballast water (Peters 1933). It spread across northern Europe to France by 1930, became phenomenally abundant in the rivers of Germany in the mid-1930s (Panning 1939, Hoestland 1948), reached the French Mediterranean via canals by 1959 (Hoestland 1959, Petit 1960), and again became abundant in Germany and the Netherlands in the 1980s (Ingle 1986; M. Türkay, pers. comm., 1995).

In England one adult *E. sinensis* and one of unreported size were collected in 1935 and 1949 and hundreds, including a few ovigerous females,

have been collected since 1976 (Ingle 1986) and are apparently now established in the Thames River (P. Clark, pers. comm., 1996). Hundreds of adults have been collected in the Baltic Sea, although salinities there are below the 25 ppt reported as necessary for successful egg development (Panning 1939). Sixty-six adults but no eggs, larvae, or juveniles have been reported from Finland (Hahtela 1963), and although three out of 33 females recorded from Denmark carried eggs, "none of the eggs were healthy or able to develop" (Rasmussen 1987). One adult was taken from the North American Great Lakes in 1965 and nine or 10 adults were collected between 1973 and 1994, most from western Lake Erie (Nepszy and Leach 1973; J. Leach, pers. comm., 1994). As in the Baltic, the Great Lakes are too fresh for successful egg development. A single adult was collected from the Mississippi River delta in Louisiana in 1987 (Horwath 1989; D. Felder, pers. comm., 1995).

Ten mechanisms for long-distance transport, two involving natural means and eight based on human activities, are theoretically available to brachyurans, though most are unlikely to have operated in bringing *E. sinensis* to California. These mechanisms are as follows:

(1) DISPERSAL OF LARVAE BY CURRENTS. Thorson (1961) calculated that it would take more than 12 months to drift passively in ocean currents from Japan to California, including a minimum crossing time between "stepping stones" (islands or shallow banks) of about 10 months. That is too long a time for *E. sinensis*, whose larval development lasts at most 3–4 months (Panning 1939, Anger 1991). Larval drift from Europe is not tenable. *Eriocheir sinensis* larval behavior also promotes retention of the larvae within an estuary (Anger 1991).

(2) DISPERSAL OF ADULTS OR JUVENILES ON FLOATING MATERIAL. Certain pelagic, neustonic crabs typically are found on floating seaweeds (such as *Sargassum*) and other floating materials on slope and deep ocean waters, including species in the genera *Planes* and *Portunus* (Williams 1984). Regarding benthic crabs, Alcock (1900) noted that *Plagusia* and *Varuna* had been found on drift timber in the open sea, specifically referencing some specimens of *Plagusia depressa tuberculata* Lamarck (= *P. d. squamosa* Alcock) collected in the Bay of Bengal and Arabian Sea (though how far offshore was not stated). How-

ever, even if it were to be carried to sea on floating debris, *E. sinensis* would be unlikely to survive transit times of over a year from source areas to California.

(3) **TRANSPORT OF ADULTS OR JUVENILES IN SHIP FOULING.** Numerous examples exist of crabs transported across or between oceans on the hulls of ships, primarily in earlier times (e.g., Buitendijk and Holthuis 1949, Carlton and Cohen 1996), including observations of crabs on the hulls of ships on the high seas or on arrival in a foreign (to the crab) port (Stebbing 1893, Alcock 1900). Opportunities for the transport of crabs on ships' hulls have decreased dramatically because of (1) the decline of wooden ships, whose hulls were often infested with shipworms and gribbles, producing deep, bored cavities capable of hosting errant organisms such as crabs (Chilton 1910), and (2) more effective antifouling coatings, increased vessel speed, and shorter time in port, which have tended to reduce the development of extensive hull-fouling communities. We know of no recent observations of crabs on the hulls of ships in normal transoceanic operation.

(4) **TRANSPORT OF ADULTS OR JUVENILES IN CARGO.** Marchand (1946) reported the transport of saber crabs, *Platychoirapsus spectabilis* (= *P. typicus* Rathbun), in a ship's cargo of cedar logs from the state of Tabasco, Mexico, to the Hillsborough River, Florida, where they became established. In Mexico the logs were floated downriver to the coast before being loaded on board ship and routinely were found to harbor crabs, snakes, and turtles on arrival in Florida. We know of no cargoes of logs or other materials arriving in San Francisco Bay in recent decades that would likely have carried live crabs.

(5) **TRANSPORT OF ADULTS OR JUVENILES ON SEMISUBMERSIBLE DRILLING PLATFORMS AND OTHER LONG-DISTANCE, SLOW-MOVING VESSELS.** Drilling platforms, ships serving as light stations (or in the past, as coaling stations), and the like may on occasion take slow, long-distance voyages, often under tow, after being anchored in one site for a lengthy period. Such vessels may develop and successfully transport an exuberant fouling growth, including crabs (e.g., Bertelsen and Ussing 1936, Benech 1978, Foster and Wilan 1979). We found no records of drilling plat-

forms or other such vessels arriving in the San Francisco Bay area in the 1980s or 1990s.

(6) **TRANSPORT OF LARVAE OR JUVENILES IN BALLAST WATER.** Ballast water—water pumped in large quantities into cargo holds or dedicated ballast tanks at the start of a voyage to achieve proper trim and buoyancy, and later discharged on arrival at a port before taking on cargo—has been implicated in the transport and introduction of numerous freshwater, estuarine, and marine species in the last several decades (Carlton 1985, Carlton and Geller 1993). Organisms introduced into San Francisco Bay via ballast water in the past two decades include two clams and numerous small crustaceans from Asia and probably many other organisms from both Asia and Europe (Cohen and Carlton 1995).

Brachyuran larvae have been collected from the ballast tanks of vessels arriving at the entrance to the St. Lawrence Seaway (Locke et al. 1991); at Australian ports (Williams et al. 1988) and Coos Bay, Oregon (Carlton and Geller 1993; J.T.C., unpubl. records), from Japan; and at Chesapeake Bay from Europe and the Mediterranean (D. Smith, M. Wonham, and G. Ruiz, pers. comm., 1995). A mitten crab was collected from the ballast tank of a ship arriving at Port Said, Egypt, from the Far East (Hoestland 1948), at least seven crab species were collected from sediments in the ballast tanks of ships arriving in Australia from Japan (Williams et al. 1988), and portunid crabs over 3 cm in carapace width were taken from the ballast tank of a European ship entering Chesapeake Bay (D. Smith, M. Wonham, and G. Ruiz, pers. comm., 1995). Although larger crabs are less likely to be taken into or discharged from ballast tanks than larvae or small juveniles because of the small size of intake screens and the damage incurred by larger organisms in passing through pumps, ships sometimes gravitate water in or out of their ballast tanks, permitting the occasional transfer of mature and even ovigerous crabs. Because cargo vessels cross from Japan to northeastern Pacific ports in 13–16 days (Carlton and Geller 1993), both larvae and adults should be capable of surviving the passage.

Estimates based on 1991 shipping data indicate that no large commercial vessels entered San Francisco Bay whose last port of call was Europe and there were about 75 whose last port

