Figure 4.35
Irregularly shaped load casts on the base of a loose slab of Cretaceous sandstone, southern Oregon coast.

tens of centimeters. Load casts may superficially resemble flute casts; however, they can be distinguished from flutes by their greater irregularity in shape and their lack of definite upcurrent and downcurrent ends. Also, load casts do not display a preferred orientation with respect to current direction.

Although they are called casts, load casts are not true casts because they are not fillings of a preexisting cavity or mold. They are formed by deformation of uncompacted, hydroplastic mud beds owing to unequal loading by overlying sand layers. Uncompacted muds with excess fluid pore pressures, or muds liquefied by an externally generated shock, can be deformed by the weight of overlying sand, which may sink unequally into the incompetent mud. Loading owing to unequal weight of the sand forces protrusions of sand down into the mud, creating positive-relief features on the base of the sandstone beds that may resemble some erosional structures, as mentioned. Load casts are closely related genetically to ball and pillow structures and flame structures. Flute and groove casts may be modified by loading, which tends to exaggerate their relief and destroy their original shapes.

Load casts can form in any environment where water-saturated muds are quickly buried by sand before dewatering can take place. They are not indicative of any particular environment, although they tend to be most common in turbidite successions. Their presence on the bases of some beds and not on others seems to reflect the hydroplastic state of the underlying mud. They apparently will not form on the bases of sand beds deposited on muds that have already been compacted or dewatered prior to deposition of the sand.

Biogenic Structures

Trace Fossils

The burrowing, boring, feeding, and locomotion activities of organisms can produce a variety of trails, depressions, and open burrows and borings in mud or semiconsolidated sediment bottoms. Filling of these depressions and burrows with sediment of a different type or with different packing creates structures that may be either positive-relief features, such as trails on the base of overlying beds, or features that show up as burrow or bore fillings on the tops of the underlying mud bed. Burrows and borings commonly extend down into beds; therefore, these structures are not exclusively bedding-plane structures.

Tracks, trails, burrows, borings, and other structures made by organisms on bedding surfaces or within beds are known collectively as trace fossils, ichnofossils, or lebensspuren. Study of trace fossils comprises the discipline of ichnology,
which has become increasingly complex since the mid-1950s and has spawned a massive body of literature. Several books that trace the evolution of ichnology during that period are listed under additional readings at the end of this chapter.

**Kinds of Trace Fossils.** Trace fossils are not true bodily preserved fossils; that is, they do not form by conversion of a skeleton into a body fossil. They are simply structures that originated through the activities of organisms. Interpreted broadly, biogenic structures can be considered to include the following: (1) bioturbation structures (burrows, tracks, trails, root penetration structures), (2) biostratification structures (algal stromatolites, graded bedding of biogenic origin), (3) bioerosion structures (borings, scrapings, bitings), and (4) excrement (coprolites, such as fecal pellets or fecal castings). Not all geologists regard biostratification structures as trace fossils, and these structures are not commonly included in published discussions of trace fossils.

Trace fossils can be assigned to several general categories on the basis of morphology (taxonomy), presumed behavior of the organism that produced the structures, and preservational process (Simpson, 1975; Frey, 1978). On the basis of morphology (shape), they can be grouped into such categories as tracks, trails, burrows, borings, shafts (dominantly vertical burrow or boring), tunnels (dominantly horizontal burrow or boring), and bioturbate texture. Bioturbate texture refers to gross texture or fabric imparted to sediments by extensive bioturbation; it typically consists of densely packed, contorted, truncated, or interpenetrating burrows or other traces few of which remain distinct morphologically. Sediment that is less crowded with burrows is said to be mottled or burrow mottled. Tracks, trails, burrows, and bioturbate texture are features formed in soft sediments. Borings are formed in hard substrates. Classification of trace fossils on the basis of the behavior of the generating organism is referred to as ethological classification. Classified this way, trace fossils are divided into categories such as resting traces, crawling traces, grazing traces, feeding traces or structures, and dwelling structures (e.g., Simpson, 1975). Trace fossils can be classified on the basis of type of preservation, using terms such as full relief, semirelief, concave, and convex (Seilacher, 1964; Martinsson, 1965). Traces formed at the sediment surface are called exogenic (outside) traces, and those formed within strata are called endogenic (inside) traces.

Trace fossils are classified into *ichnogenera* on the basis of characteristics that relate to major behavioral traits and are given generic names such as *Ophiomorpha*. Distinctive but less important characteristics are used to identify *ichnospecies*, e.g., *Ophiomorpha nodosa*. The formal nomenclature for trace fossils has grown haphazardly over the years. Perusal of trace-fossil literature suggests that identifying and naming ichnogenera and ichnospecies is complex and controversial. Complexities arise because (1) the same individual organism or species of organism can produce different structures corresponding to different behavioral patterns, (2) the same burrow may be differently preserved in different strata, (3) different tracemakers may produce identical structures when behaving similarly, and (4) multiple tracemakers may produce a single structure (Bromley, 1996, p. 155).

Trace fossils are produced by a host of marine organisms such as crabs, flatfish, clams, molluscs, worms, shrimp, and eel. In nonmarine environments organisms such as insects, spiders, worms, millipedes, snails, and lizards can produce a variety of burrows and tunnels; vertebrate organisms leave tracks; and plants leave root traces. Freshwater fluvial and lacustrian environments are inhabited by organisms such as worms, crustaceans, insects, bivalves, gastropods, fish, birds, amphibians, mammals, and reptiles that can produce various kinds of traces. The organisms that produce traces are rarely preserved with the traces; thus, the trace maker is commonly not known. Therefore, the names applied to ichnogenera and
ichnospecies generally do not refer to the trace makers themselves. Trace fossils are present in sedimentary rocks ranging in age from Precambrian to Tertiary. The total diversity (number of different kinds) of trace fossils is low in Precambrian rocks but shows a significant increase in Cambrian rocks. Ordovician rocks show another increase, followed by approximately constant total diversity in rocks formed during the remaining part of the Paleozoic, Mesozoic, and Tertiary (Crimes, 1992).

Trace Fossil Assemblages. From a sedimentological standpoint, study of trace-fossil assemblages has commonly proven to be more useful than study of individual ichnogenera or ichnospecies. A trace-fossil assemblage is a basic collective term that embraces all of the trace fossils present within a single unit of rock. Although various kinds of trace-fossil assemblages are recognized, grouping of trace fossils into ichnofacies has particular significance in paleoenvironmental studies. Seilacher (1964, 1967) introduced the concept of ichnofacies to describe associations of trace fossils that are recurrent in time and space, and that reflect environmental conditions such as water depth (bathymetry), salinity, and the nature of the substrate in or on which they formed (e.g., mud vs. sand bottom). Fundamentally, ichnofacies are sedimentary facies defined on the basis of trace fossils, and each ichnofacies may include several ichnogenera.

Seilacher (1967) established six ichnofacies, which he named after characteristic ichnogenera. Four of these (Skolithos, Cruziana, Zoophycus, and Nerites) were based on the marine water depth at which they were interpreted to occur (Table 4.2; Fig. 4.36). The Glossifungites ichnofacies was established for traces that occur in firm to hard marine surfaces, and the Scyenia ichnofacies characterized non-marine environments. Subsequently, Frey and Seilacher (1980) established the Trypanites ichnofacies for hardgrounds and rockgrounds, Bromley et al. (1984) proposed the Teredolites ichnofacies for borings in wood (woodgrounds), and Frey and Pemberton (1987) established the Psilonichus ichnofacies for softgrounds in the marine to nonmarine environment. Several additional ichnofacies have also been proposed (e.g., Bromley, 1996, p. 241); however, the nine ichnofacies shown in Table 4.2 are most commonly used. Sedimentologists are particularly interested in the Skolithos, Cruziana, Nerites, and Zoophycus ichnofacies, which have the greatest potential for interpreting ancient marine environmental conditions.

Skolithos Ichnofacies. Trace fossils of this association are characterized especially by vertical, cylindrical or U-shaped burrows (e.g., Ophiomorpha, Diplacasterion, and Skolithos, Fig. 4.37). Overall diversity of ichnogenera is low and few horizontal structures are present. This ichnofacies is developed primarily in sandy sediment where relatively high levels of wave or current energy are typical. Organisms in this environment construct deep burrows to protect against desiccation or unfavorable temperature or salinity changes during low tide, and as a means of escaping the shifting substrate of the surface (Pemberton et al., 1992). The Skolithos ichnofacies is typical of sandy shoreline environment (Fig. 4.36), but it may grades seaward into shallow shelf environments. It has also been reported from some deeper-water environments, such as deep-sea fans and bathyal slopes.

Cruziana Ichnofacies. The Cruziana ichnofacies commonly occurs in somewhat deeper water than the Skolithos ichnofacies within subtidal zones below fair-weather wave base but above storm wave base (Frey and Seilacher, 1980), typical of the middle and outer shelf. It may also be present in sediments from some nearshore environments. It is characterized by a mixed association of traces that may include nearly vertical burrows, inclined U-burrows (Rhizocorallium), horizontal structures (Cruziana), the traces of organisms that move about on or near the sediment surface (Thalassinoides), and other odd traces having star shapes.
<table>
<thead>
<tr>
<th>Ichnofacies</th>
<th>Nature of Substrate</th>
<th>Environment</th>
<th>Water Depth</th>
<th>Water Energy</th>
<th>Distinguishing Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teredolites</td>
<td>Woodground</td>
<td>Estuarine, nearshore marine</td>
<td>—</td>
<td>—</td>
<td>Club-shaped, stumpy to elongate, subcylindrical to subparallel borings</td>
</tr>
<tr>
<td>Trypanites</td>
<td>Rockground</td>
<td>Rocky coasts, reefs, hard-grounds</td>
<td>—</td>
<td>—</td>
<td>Cylindrical, tear-, or U-shaped, vertical to branching borings</td>
</tr>
<tr>
<td>Scoyenia</td>
<td>Firmground</td>
<td>Freshwater, terrestrial</td>
<td>—</td>
<td>—</td>
<td>Horizontal to curved or tortuous burrows; sinuous crawling traces, vertical cylindrical to branching shafts; tracks and trails</td>
</tr>
<tr>
<td>Glossifungites</td>
<td>Firmground</td>
<td>Marine to nonmarine</td>
<td>Various</td>
<td>Various</td>
<td>Vertical, cylindrical, U- or tear-shaped borings and/or densely branching burrows</td>
</tr>
<tr>
<td>Psilonichus</td>
<td>Softground sand, mud</td>
<td>Marine to nonmarine</td>
<td>—</td>
<td>—</td>
<td>J-, Y-, or U-shaped burrows; vertical shafts and horizontal tunnels; tracks, trails, root traces</td>
</tr>
<tr>
<td>Skolithos</td>
<td>Softground sand</td>
<td>Marine</td>
<td>Beach</td>
<td>High</td>
<td>Vertical, cylindrical or U-shaped burrows; very few horizontal burrows; low diversity</td>
</tr>
<tr>
<td>Cruziana</td>
<td>Softground sand, mud</td>
<td>Marine</td>
<td>Lagoon, shelf</td>
<td>Medium to low</td>
<td>Mixed association of vertical, inclined, and horizontal structures; high diversity of traces</td>
</tr>
<tr>
<td>Zoophycus</td>
<td>Softground mud</td>
<td>Marine</td>
<td>Slope-abyssal</td>
<td>Low</td>
<td>Simple to moderately complex grazing and feeding structures; horizontal to slightly inclined feeding or dwelling structures arranged in delicate sheets, ribbons, lobes or spirals</td>
</tr>
<tr>
<td>Nereites</td>
<td>Softground sand, mud</td>
<td>Marine</td>
<td>Slope-abyssal</td>
<td>Turbidity current event</td>
<td>Complex horizontal, crawling and grazing traces and patterned feeding/dwelling traces; low diversity</td>
</tr>
</tbody>
</table>

Data from: Bromley et al., 1984; Frey and Seilacher, 1983; Frey and Pemberton, 1987; Pemberton et al., 1992; Seilacher, 1967.
Figure 4.36
Schematic representation of the relationship of characteristic trace fossils to sedimentary facies and depth zones in the ocean. Borings of 1, Polydora; 2, Entobia; 3, echinoid borings; 4, Trypanites; 5, 6, pholadid burrows; 7, Diplocraterion; 8, unlined crab burrow; 9, Skolithos; 10, Diplocraterion; 11, Thalassinoides; 12, Arenicolites; 13, Ophiomorpha; 14, Phycodes; 15, Rhizocorallium; 16, Teichichnus; 17, Crossopodia; 18, Asteriacites; 19, Zoophycos; 20, Lorenzinia; 21, Zoophycos; 22, Paleodictyon; 23, Taphrhelminthopsis; 24, Helminthoida; 25, Spirophage; 26, Cosmorhaphe. [From Ekdale, A. A., R. C. Bromley, and S. B. Pemberton, 1984, Ichnology: Trace fossils in sedimentology and stratigraphy: Soc. Econ. Paleontologists and Mineralogists Short Course No. 15, Fig. 15.2, p. 187, reprinted by permission of SEPM, Tulsa, OK. Modified from Crimes, T. P., 1975, The stratigraphical significance of trace fossils, in Crimes, T. P., and J. C. Harper (eds.), The study of trace fossils, Fig. 7.2, p. 118: Springer-Verlag, New York. Reproduced by permission.]

(Asteriacites) or C-shapes (Arenicolites) (Fig. 4.38). Note: some authors (e.g., Bromley, 1996, p. 249) recognize a separate Arenicolites ichnofacies. The Cruziana ichnofacies commonly has high diversity and abundance of traces (Fig. 4.38); in fact, a profusion of burrows may be present. It is typically developed in well-sorted silts and sands, but it may be present in muddy silts or sands.

Zoophycus Ichnofacies. This ichnofacies appears most typical of quiet-water environments with moderately low oxygen levels and muddy bottoms but can occur in other substrates. It is characterized by traces that range from simple to moderately complex, such as Spirophyton (Fig. 4.39). Individual traces may be abundant, but overall diversity is low. Sediments of the Zoophycos ichnofacies may be totally bioturbated (Bromley, 1996, p. 250). Although commonly considered to be indicative of deeper water (Fig. 4.36), it is known to occur also in shallow water. Thus, its value as a paleodepth indicator is problematical. Its distribution appears
to be tied more closely to oxygen levels and bottom sediment type than water depth.

**Nerites Ichnofacies.** The *Nerites* ichnofacies is characteristic of deep water and is apparently restricted to turbidite deposits. It is distinguished by complex horizontal crawling and grazing traces and patterned feeding/dwelling structures. The ichnogenera are ornate and complicated, such as *Paleodictyon*, *Spirorhabdus*, and *Nerites* (Fig. 4.40). Total diversity of traces is high, but the abundance of individual traces is low. The *Nerites* ichnofacies develops initially in sandy (turbidite) substrates but may later colonize parts of some muddy (pelagic) deposits that form on top of sandy turbidites.

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**Figure 4.37**

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**Figure 4.38**
Sedimentary Structures

Figure 4.39

Other Ichnofacies. The Psilonichnus ichnofacies (Fig. 4.41) is a softground ichnofacies developed under nonmarine to very shallow marine or quasi-marine conditions. It is characterized by J-, Y-, or U-shaped burrows of marine organisms, vertical shafts, and horizontal tunnels of insects and tetrapods, tracks and trails of insects, reptiles, birds, and mammals, and root traces. The other ichnofacies listed in Table 4.2 are distinguished by development in firm, but uncemented substrates, rocky substrates, or woody material. Scoyenia ichnofacies, which occur in both terrestrial and aquatic environments, are characterized by diverse traces that include small, horizontal, curved, or tortuous feeding burrows, sinuous crawling traces, tracks, trails, and vertical cylindrical to irregular shafts. The Trypanites ichnofacies develops in fully lithified marine substrates (beachrock, rocky coasts, hardgrounds, reefs). Traces include cylindrical, tear-, or U-shaped borings, commonly vertical to branching; most of which are dwelling structures for suspension-feeding organisms (Fig. 4.36, 1–4). Other structures in this ichnofacies include rasping and scraping traces made by feeding organisms, holes drilled by predatory gastropods, and microborings made by algae and fungi. The Glossifungites ichnofacies develops in a variety of marine environments in firm, but unlithified,
substances that typically consist of dewatered, cohesive muds. It is characterized by vertical, cylindrical, U- or tear-shaped borings and/or densely branching burrows of suspension feeders or carnivores such as shrimp, crabs, worms, and pholadid bivalves (Fig. 4.36, 5-8). Individual structures may be abundant but diversity is low. *Teredolites* ichnofacies are restricted to woody substrates (so-called woodground) commonly in estuarine or very nearshore environments where substantial amounts of woody material can accumulate on the bottom. The traces consist of profuse club-shaped borings that may be stumpy to elongate, and subcylindrical to subparallel.

**Significance of Trace Fossils**

**Paleoenvironmental Indicators.** Trace fossils are important paleoecological indicators; however, they are not infallible paleodepth indicators. In general, organisms in the littoral or intertidal zones adapt to harsh conditions resulting from high wave or current energy, desiccation, and large temperature and salinity fluctuations by burrowing into sand to escape. Thus, vertical and U-shaped dwelling burrows, some with protective linings, characterize the *Skolithos* ichnofacies of the neritic zone. The neritic zone or subtidal zone extending from the low-tide zone to the edge of the continental shelf (at about 200-m water depth) is a less demanding environment, although erosive currents may be present. Vertical dwelling burrows and protected, U-shaped burrows are less common in this zone. Burrows tend to be shorter, and surface markings made by organisms such as crustaceans (or trilobites during early Paleozoic time) are more common. In the deeper part of the neritic zone, organic matter becomes abundant enough for sediment feeders to become established and produce feeding burrows. In these deeper waters, vertical escape or dwelling burrows thus tend to give way to horizontal feeding burrows. This zone of the ocean is distinguished by the *Cruziana* ichnofacies, characterized by such traces as those shown in Figure 4.36, 14-18 and Fig. 4.38. The deep bathyal and abyssal zones of the ocean exist below wave base where low-energy conditions generally prevail, although erosion and deposition can occur in these zones owing to turbidity currents or deep-bottom currents. Complex feeding burrows, such as those of the *Nereites* ichnofacies (Fig. 4.36, 22-26; Fig. 4.40), are particularly common in these zones.

Although each of these marine ichnofacies tends to be characteristic of a particular bathymetric zone of the ocean as shown in Figure 4.36, we now know that individual trace fossils can overlap depth zones. No single biogenic structure is an infallible indicator of depth and environment. The basic controls on the formation of trace fossils include nature of the substrate, water energy, rates of deposition, water turbidity, oxygen and salinity levels, toxic substances, and quantity of available food (Pemberton, MacEachern, and Frey, 1992).

Trace fossils should be studied as assemblages of structures in conjunction with other physical, chemical, and biological characteristics of the same substrates. Trace fossils occur in rocks of all ages, including some Precambrian rocks. They have been reported in most types of sedimentary rocks except evaporites.
and rocks deposited in highly reducing (euxinic) environments. Highly saline environments or euxinic environments, where toxic conditions are caused by lack of oxygen and the presence of hydrogen sulfide gas, preclude or greatly reduce organic activity. Studies of bioturbation in modern open-ocean environments show that organisms may rework sediment so thoroughly that primary laminations and other physically produced structures are completely destroyed in most environments where enough oxygen is present for organisms to flourish. Exceedingly intense bioturbation can produce bedding that is so homogenized that it has a mottled or stirred appearance or is completely devoid of all structures. For bedding and other physically produced sedimentary structures to escape destruction by biogenic activity and become preserved in the geologic record, they must be formed either in an environment where sedimentation rates are so high that organisms do not have time to rework sediments and destroy original structures or in euxinic environments or highly saline environments, as mentioned, where organic activity is limited.

Other Applications. In addition to their usefulness as environmental indicators, trace fossils are also useful in several other ways. They may, for example, serve as an indicator of relative sedimentation rates based on the assumption that rapidly deposited sediments contain relatively fewer trace fossils than slowly deposited sediments. They can also help to show whether sedimentation was continuous or marked by erosional breaks, and they provide a record of the behavior patterns of extinct organisms. They may even be useful in paleocurrent analysis; study of the orientation of resting marks of organisms that may have preferred to face into the current while resting establishes the paleocurrent-flow direction. Some trace fossils such as U-shaped burrows, which opened upward when formed, can be used to tell the top and bottom orientation of beds. Trace fossils also have biostratigraphic and chronostratigraphic significance for zoning and correlation, and they may be useful for recognition of bounding discontinuities between stratigraphic sequences (Pemberton, MacEachern, and Frey, 1992; also see Frey and Pemberton, 1985, and Frey and Wheatcroft, 1989).

Stromatolites

Stromatolites are organically formed, laminated structures composed of fine silt- or clay-size sediment or, more rarely, sand-size sediment. Most ancient stromatolites occur in limestones; however, stromatolites have also been reported in siliciclastic sediments. Stromatolitic bedding ranges from nearly flat laminations that may be difficult to differentiate from sedimentary laminations of other origins to hemispherical forms in which the laminae are crinkled or deformed to varying degrees (Fig. 4.42). The hemispherical forms range in shape from biscuit- and cabbage-like forms to columns. Logan, Rezak, and Ginsburg (1964) classified these hemispherical stromatolites into three basic types: (1) laterally linked hemispheroids; (2) discrete, vertically stacked hemispheroids: and (3) discrete spheroids, or spheroidal structures (Fig. 4.43). Laterally linked hemispheroids and discrete, vertically stacked hemispheroids can combine in various ways to create several different kinds of compound stromatolites. The term thrombolite was proposed by Aitken (1967) for structures that resemble stromatolites in external form and size but lack distinct laminations. The laminations of stromatolites are generally less than 1 mm in thickness and are caused by concentrations of fine calcium carbonate minerals, fine organic matter, and detrital clay and silt. Stromatolites composed of quartz grains have also been reported (Davis, 1968).

Stromatolites were considered true body fossils by early workers, but they are now known to be organosedimentary structures formed largely by the trapping and binding activities of blue-green algae (cyanobacteria). They are forming