the closed channel lies below the open channel, the fermions form a bound pair that includes both closed- and open-channel contributions. As the resonance is approached from below, the closed channel component is reduced. The pair grows in size toward infinity (see the figure, inset). Above resonance, the fermion pair remains unbound.

The situation for many fermions is very different from that for two fermions. The current BCS-BEC crossover theory (*12*) gives the following picture. As the resonance is approached from below, the pairs grow in size and overlap. At resonance, the pair size is reduced to interparticle spacing, independent of the details of atomic potentials. This is remarkable because it implies that all Fermi gases with the same density have identical properties at resonance, even though their atomic interactions are very different. Such universality was observed in 2003 (*13*, *14*). Above resonance, fluctuations between closed- and open-channel states continue to bind fermions into pairs, although the binding force decreases with increasing distance from resonance, and the pairs become much larger than interparticle spacing (see the figure).

With increasing temperature, the superfluid will be destroyed by thermal effects. The destruction takes place sharply at a temperature T_c at which the pairs stop acting in unison, such that the system loses "phase coherence." Bound pairs can still exist above T_c, but they will break up gradually as temperature increases. The region above T_c with a substantial number of bound pairs is referred to as the pseudo-gap region.

In the experiment by Chin *et al*., a radial frequency radiation is applied to a Fermi gas of ^{6}Li consisting of equal numbers of fermions in atomic states **1** and **2**. The radiation excites **2** to a different atomic state **3**. If there is no pairing between **1** and **2**, only radiation with frequency equal to the energy difference between **2** and **3** will be absorbed. If there is pairing, another absorption frequency will appear, corresponding to the breakup of the pair **1**+**2**. Such a double-peak structure is indeed observed as the temperature is lowered. Moreover, the atomic peak (due to **2**-to-**3** transition) gradually disappears at lower temperatures, leaving only the "pairing" peak, which implies that all fermions are transformed into pairs [see figure 3 in (*8*)]. This behavior above resonance provides strong evidence for a fermion superfluid, because there are no stable closed-channel molecules in that regime, and the pairs must come from pairing in an open channel. Kinnunen *et al*. show that these phenomena are well accounted for by theoretical calculations based on the BEC-BCS crossover picture (*9*).

The discovery of a Fermi superfluid will not only enable the study of many difficult problems in solid-state physics in well-controlled settings; it will also further strengthen the cold atom connection to other fields such as nuclear physics and quantum information theory. Research into fermion superfluids is only just beginning, but even at this early stage, new and exciting directions are emerging. A recent preprint (*15*) reported reversible production of "*p*-wave" molecules across Feshbach resonance. These are molecules that carry orbital angular momentum. Even fermion superfluids with rotating pairs may be possible in the near future. The best is yet to come.

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PALEOBIOLOGY

Decoding the Ediacaran Enigma

Martin Brasier and Jonathan Antcliffe

Fossils and Egyptian hieroglyphs share daunting similarities: Both consist of arcane geometries, glyphs in rock that conceal deeper meanings from the rude enquirer, and are capable of false translation. Remember Shelley's fakery "*And on the pedestal the words appear: 'My name is Ozymandias, King of Kings: Look on my works ye Mighty and despair!*" and take note of recent fossil feuds (*1*, *2*). To read the fossil runes correctly, the paleontologist craves the stimulus of fresh fossil finds, channeled by insightful methodology to catalyze productive thought. The recent discovery of remarkably well-preserved, three-dimensional Ediacaran fossils in Newfoundland reported by Narbonne (*3*) on page 1141 of this issue may provide such a stimulus. The new fossil find raises the question of whether the study of the life history and growth plan of these fossil animals could provide a Rosetta stone for decoding Ediacaran animal evolution (*4*–*6*).

The Ediacara biota remains one of the greatest enigmata within evolutionary paleobiology (see the figure, top). Discovered in 1946 by R. C. Sprigg in the Flinders Ranges of southern Australia, the Ediacara biota—which is 580 to 543 million years old (Ma)—represents the most ancient complex organisms on Earth. Martin Glaessner provided the first insights into Ediacaran biology (*7*). He saw in the fossils of Ediacaran animals (so remarkably preserved in late Precambrian sandstones) the ancestors of Phanerozoic animal phyla. The Cambrian is the first period with abundant fossils and marks the start of the era of the Phanerozoic or "visible life" that continues through to the present. Before this came the vast interval of the Precambrian, which ranges back to the origins of the Earth about 4600 million years ago.

Paleontologists eagerly sought relationships between Ediacaran fossils and living seapens and worms, jellyfish and crabs. This "great ancestral" view has held sway for almost 40 years (*8*, *9*), but a growing number of paleontologists argue that Ediacaran creatures were not ancestral to Cambrian life at all. They suggest that members of the Ediacara biota were uniquely fashioned beasts that met their doom at the end of the Precambrian (*10*–*12*). Ediacaran animals—each "quilted" like a mattress—take many forms, resembling desiccated lichens, underwater fungi, enormous ferns, or giant deep-sea single-celled protists (*10*–*12*).

We believe the time has come to raise difficult questions about the methodology used to analyze Ediacaran fossils. Ediacaran forms once thought to be "jellyfish" by Glaessner (*7*) have been reinterpreted as the attachment discs of fernlike fronds (*13*). And fronds once placed in discrete taxa now seem to be part of a much wider spectrum of intergrading forms (*3*). Could it be that other "Glaessnerian species" are not biological species in the sense of Mayr (*14*) at all, but mere organs, different growth stages, or ecophenotypes of a single taxonomic unit? For example, the archetypal taxon of the Ediacara biota is a frondlike (frondose) organism called *Charnia*. In this organism, each "branch" of the frond is further subdivided at least three times into tiny, self-similar *Rangea*-like elements called rangeo-

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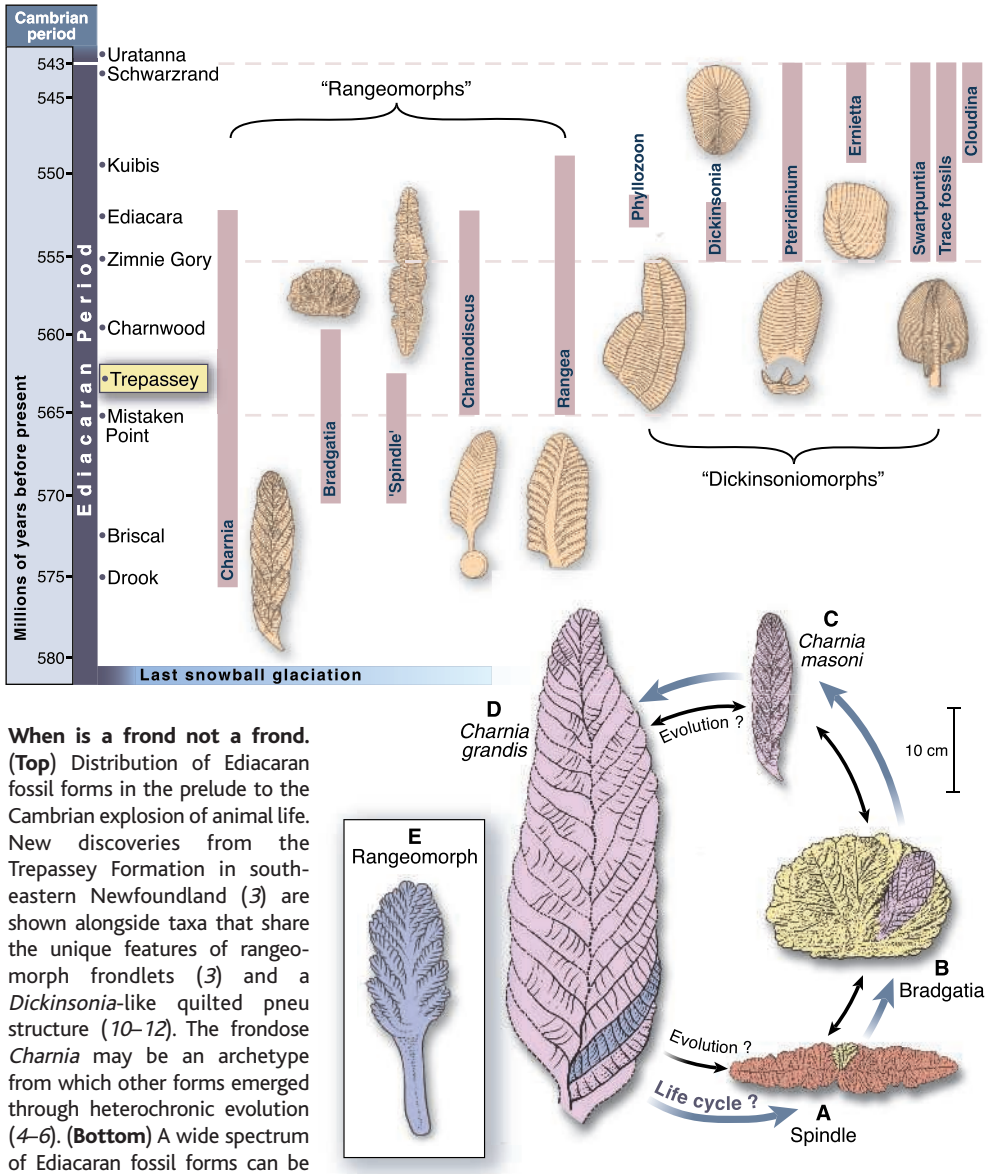
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morph frondlets by Narbonne (*3*). In *Charnia*, these rangeomorph frondlets appear to be folded over so that only half is visible from one side (see lower figure, D). Both small (about 0.2 m) and large (>0.7 m) specimens of *Charnia* frond are known to coexist in England (see lower figure, C and D), and even smaller *Charnia*-like units can also be seen clustered together within the coexisting bushlike fossil *Bradgatia* (see lower figure, B). In Newfoundland, coexisting fossil "spindles" contain rows of little *Bradgatia*-like bushes, each branch of which looks like a tiny *Rangea* (see lower figure, A). Could these intergrading rangeomorphs represent different stages of the *Charnia* growth cycle, with bushlike forms (such as *Bradgatia*) and spindle-shaped forms acting as a creche that produces other forms, and large *Charnia grandis* surviving as an example of gigantism? If such intergradation can be proved, what does this imply about the biology of the Ediacara biota? This question tests our assumptions about the fundamental unit of Ediacaran fossil architecture: Is it the *Charnia* frond, the rangeomorph frondlet (*3*), or the smaller quilted pneu (*10*–*12*)?

Our concern is that the current "Ediacaran species concept" is no longer tenable. It is based on a "typological" approach using type specimens rather than populations (*14*), and on an "analog" approach that compares fossil morphologies with modern organisms according to assumed similarities. But these similarities could well have evolved independently. This approach is therefore unsound for deciphering long-extinct groups and, unlike cladistics, is an insecure basis for classification. We need quantitative studies of fossil populations, with analysis of morphological gradients in the same geological successions and bedding planes (*15*), as well as detailed analyses of growth programs (morphospace), life history (ontogeny), and evolutionary history (phylogeny) (*4*–*6*). It is premature to put forth any evolutionary history for fossils whose diagnosis has been conceived without reference to a postulated growth program observed through successive stages of ontogeny. Without such reference, both the taxonomic pattern and the evolutionary processes responsible for it will remain obscure.

Several recent studies reveal the dangers of the popular "analog" approach. Extant frondose seapens, which often provide a model for extinct Ediacaran fronds (*8*, *9*), comprise colonies of coral-like polyps that multiply by the antapical insertion of branches around the base of the colony; the Ediacaran *Charnia* most likely grew by apical insertion of these elements (*4*–*6*). Xenophyophores, which provide yet another model for Ediacaran fronds (*10*–*12*), are larger benthic forams that grow in quite another way (*4*, *6*). The fields of morphospace that each of these groups occupies are different so that similarities among Ediacaran fossils, seapens, and xenophyophores may be convergent and misleading (*4*–*6*).

How then can we decode the evolution of the long-extinct Ediacara biota? As with the Rosetta stone, one may begin with a well-known "cartouche" or pattern from the fossil record—in this case, the pattern of "heterochronic evolution." Many extinct fossil groups—such as the younger graptolites after the Cambrian and larger foraminifera after the Devonian (*16*, *17*)—ran a predictable evolutionary race in which architectural novelty arose through accentuation of adult or juvenile growth stages (heterochrony). Such evolutionary trends are often iterative and convergent. Do the Ediacaran fossils follow this trend? We can only answer this question by tracing changes in the fossil record over time that are consistent with heterochronic evolution. *Charnia*, the core taxon of the Ediacaran Period, is found throughout most



When is a frond not a frond. (**Top**) Distribution of Ediacaran fossil forms in the prelude to the Cambrian explosion of animal life. New discoveries from the Trepassey Formation in southeastern Newfoundland (*3*) are shown alongside taxa that share the unique features of rangeomorph frondlets (*3*) and a *Dickinsonia*-like quilted pneu structure (*10*–*12*). The frondose *Charnia* may be an archetype from which other forms emerged through heterochronic evolution (*4*–*6*). (**Bottom**) A wide spectrum of Ediacaran fossil forms can be found clustered in the same geological bedding plane. Depicted are four such forms from the new fossil finds in Newfoundland, as well as fossil forms found in England, Russia, and Australia (*3*–*6*, *15*). Their intergrading morphologies may be related in one of three ways: through growth stages within the whole life cycle (ontogeny), ecologically controlled phenotypes, or sister taxa that have evolved by suppressing or expanding different parts of the life cycle (heterochrony). The basal segments of *Charnia grandis* are reconstructed to show up to four levels of inferred "fractal" quilting. The fossils are shown at a comparable scale except the rangeomorph frondlet [Inset (E), 4 cm long].

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of the 40 million years that define this period. Early Ediacaran fossil assemblages from Newfoundland and England (dated 580 to 559 Ma) contain clustered colonies of *Charnia*-like elements—called rangeomorphs by Narbonne (*3*), or *Rangea* and *Bradgatia* by others—which are bushlike, plumose, or fusiform (see the figure, top). Late assemblages, such as those from Namibia dated at 549 to 543 Ma, lack these rangeomorph colonies. Instead, they contain a variety of simpler forms (called "dickinsoniomorphs") such as *Pteridinium* and *Ernietta*, whose architecture resembles simplifications of the archetypal *Charnia* (see the figure, top). Assemblages of intermediate age from Russia and Australia also tend to contain simple "dickinsoniomorphs" such as *Phyllozoon* and *Dickinsonia* (see the figure, top).

Perhaps innovations in Ediacaran body architecture about 580 to 543 Ma were enabled by a process of developmental change in which some aspects of *Charnia* morphology were suppressed (see the figure, bottom) while others became enhanced and dominant. Such heterochronic forms could have exploited different modes of existence—from tethered or reclining on the sea floor (older assemblages) to forms embedded in the sediment (younger assemblages), or from offshore to onshore habitats (*4*–*6*, *10*–*12*, *15*, *18*). Each of these modes of existence requires that some kind of evolution took place. If this sequence of evolutionary development (heterochrony) is correct, then perhaps we are about to break the code to the evolution of the Ediacara biota, the earliest animals. Watch this space.

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CHEMISTRY

Zinc-Zinc Bonds: A New Frontier

Gerard Parkin

The ability of metal atoms to bind to other atoms of the same element in molecular compounds plays an important role in chemistry. Furthermore, the nature of such "homonuclear" metal-metal bonds is often unusual. For example, molybdenum and tungsten can form metal-metal quadruple bonds (*1*), compared to the triple-bond maximum for nonmetals. Other metals, such as gold, can form metal-metal bonds even when there are no unpaired electrons available to do so (*2*).

However, not all metals readily form homonuclear metal-metal bonds. Zinc is one metal that was not known to form such bonds—until now. On page 1136 of this issue, Resa *et al.* (*3*) report the synthesis and structure of the dinuclear pentamethylcyclopentadienyl (Cp*) compound $Cp^*_2Zn_2$, a landmark discovery in the chemistry of zinc (see the figure).

To place this result in context, compare the chemistry of zinc with that of the other two elements in group 12 of the periodic table, cadmium and mercury. In marked contrast to zinc, compounds with mercury-mercury bonds are quite common. Hg_2Cl_2—called "calomel" and used in electrochemistry and early medicines (such as laxatives)—is one of many compounds with a dinuclear $[Hg_2]^{2+}$ core (*4*).

Progressing up the periodic table from mercury to cadmium, the ability to form metal-metal bonded compounds diminishes rapidly. The first structurally characterized compound with cadmium-cadmium bonds, $Cd_2(AlCl_4)_2$, was reported as recently as 1986 (*5*). It is therefore no surprise that compounds with zinc-zinc bonds have been elusive.

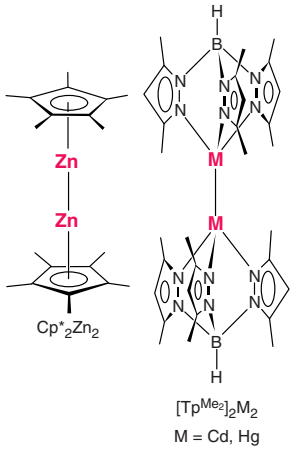
Resa *et al.* obtained their zinc-zinc bonded compound by reacting Cp^*_2Zn with Et_2Zn at –10°C in diethyl ether solution (*3*). As noted by the authors, the formation of $Cp^*_2Zn_2$ is unforeseen, requiring the formal loss of two ethyl radicals (the fate of which was not determined). In view of the unprecedented nature and unusual synthesis of $Cp^*_2Zn_2$, Resa *et al.* have given considerable attention to its characterization, particularly to the possibility that it could be the hydride-bridged derivative $[Cp^*Zn(\mu\text{–}H)]_2$. Such caution is warranted because the Co–Co bond in the cobalt analog $Cp^*_2Co_2$ (*6*) was later shown to be bridged by three hydride ligands (*7*).

It is experimentally very difficult to disprove the presence of a bridging hydride ligand (especially by x-ray diffraction), but excellent evidence is provided by the high-resolution mass spectrum, which is consistent with the formula of $Cp^*_2Zn_2$ and not with that of $[Cp^*Zn(\mu\text{–}H)]_2$. The possibility that the compound could be the hydride complex and lose H_2 in the gas phase is discounted by the fact that $Cp^*_2Zn_2$ may be sublimed without much decomposition.

Structural evidence for the absence of hydride bridges is provided by the observation that the zinc-zinc bond length in $Cp^*_2Zn_2$ is 2.31 Å, much shorter than the value of 2.45 Å in a known hydride-bridged dimer (*8*). For further comparison, the cadmium-cadmium bond length in $Cd_2(AlCl_4)_2$ is 2.58 Å (*5*), and mercury-mercury bond lengths are typically between 2.49 and 2.67 Å (*4*). The shorter zinc-zinc bond distance in $Cp^*_2Zn_2$ is in line with the single-bond metallic radii of Zn (1.25 Å), Cd (1.41 Å), and Hg (1.44 Å).

Resa *et al.* also provide chemical evidence against the formulation as a hydride compound. For example, alcoholysis of $Cp^*_2Zn_2$ is accompanied by the deposition of metallic zinc; if the compound were a hydride-bridged dimer, alcoholysis would not be expected to be accompanied by deposition of zinc, but rather by elimination of H_2.

An often cited analog of the Cp* ligand is the tris(pyrazoly)hydroborato (Tp) ligand. Both are five-electron donors in their neutral form and occupy three coordination sites. The dinuclear compounds $[Tp^{Me}_2]_2Cd_2$ (*9*) and $[Tp^{Me}_2]_2Hg_2$ (*10*) have previously been synthesized (see the figure). The work of Resa *et al.* raises the intriguing possibility that the



The first zinc-zinc bond. The molecular structure of the first molecular compound with a zinc-zinc bond (**left**) and related compounds with cadmium-cadmium and mercury-mercury bonds (**right**).

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