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HEINZ A. LOWENSTAM
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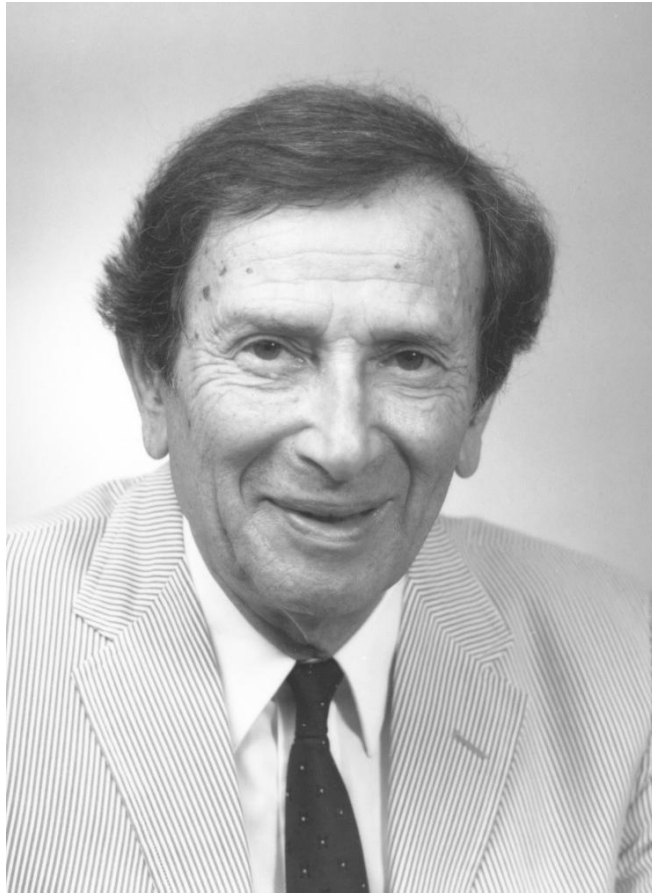
A Biographical Memoir by

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Courtesy of Dr. Lillian L. Weizner

HEINZ A. LOWENSTAM

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BY JOSEPH L. KIRSCHVINK

Heinz Lowenstam described himself as a professional beachcomber, but in fact he was among the 20th century's most superb natural scientists. Building upon an early interest in minerals and fossils gained during his childhood playing on mining dumps in Germany, he was the first to blend biological and paleontological analyses to unravel the ecological associations of fossil communities. After being denied his Ph.D. from Nazi-controlled universities for the crime of being Jewish, he fled with his wife to the United States and managed to complete his degree at the University of Chicago just prior to the start of WWII. Classified as an 'enemy alien', he contributed to the American war effort by developing paleoecological techniques to locate oil-bearing coral reefs in the sub-surface of the greater Chicago area. Rather than profiting personally from his work, Heinz published it freely in the open literature.

In the post-war isotope frenzy at the University of Chicago, Heinz was drafted as the 'Atomic Paleontologist' for Harold Urey's research group. His initial role was to provide pristine fossil materials for isotopic paleotemperature determinations, but his involvement grew rapidly to include that of

identifying the most important scientific questions about Earth's past biosphere that could be addressed for the growing field of stable isotope geochemistry. In the process of finding unaltered fossil materials, Heinz also began to wonder about the process of biomineralization itself: How do animals make minerals under biological control? How do they control the mineral composition, crystallinity, and particle size? Using his talents as a naturalist, and exploiting advances in analytical techniques, Heinz nearly doubled the known diversity of minerals produced by organisms. One of his discoveries – the biomineralization of magnetite (Fe_3O_4) in the teeth of Polyplacophoran mollusks (the chitons) – has been crucial for understanding topics as diverse as the geophysics of marine sediment magnetization and the biophysical basis of magnetoreception in animals.

Heinz was born in 1912 in Upper Silesia, in what was then southeastern Germany but is now south-central Poland, in the town of Siemjanowiz. This was a suburb of Laurahutte, a mining district with a steel mill. In his oral history recorded for the Caltech Archives, Heinz described his birthplace as

a horrible region It was like Dante's Inferno. Across the whole horizon, you saw belching chimneys spewing out fumes from lead smelters, and steel mills. There were coal mines and iron foundries. The air was so poor that our plants in the house had to be specially tended so they didn't die from the fumes As a kid, I played on a mine dump – you know, the stuff that goes out from a lead and zinc mine. I wasn't supposed to go there, but I went with some miner's kids, and we played. We normally picked up a rock to throw, and one day the one that I picked up was awfully heavy. I knew it couldn't be an ordinary rock, so I broke it. It looked like silver. It was galena – lead ore. And that's what started me initially to collect minerals.

Many of Heinz's interests in Nature clearly stem from his parents (Frieda and Kurt Löwenstamm), although neither of them had a university education. Before World War I, his

mother was the art editor of a newspaper, and wrote poetry. She encouraged Heinz's interest in nature by taking him around and showing things, and getting semi-popular publications on natural history. Heinz notes that she "... *was interested, among other things, in ancient Egypt, and she taught herself to read hieroglyphics. We would go to museums, like in Berlin, and she would read the inscriptions just like that and translate them.*" His father was similarly educated, in the sense that he was a classicist. "*He went to the Gymnasium – the German academic high school. He always had pockets full of books. He was more interested in history and literature.*" His grandfather had written a 6-volume history of the Jewish people, and most members of his family studied languages and literature. Later in life Heinz would often comment on this peculiar background with statements like, "*Ha, ha, ha, ... you know I'm the black sheep of the family; I don't shpeak any lankvages.*"

Upper Silesia was also politically unstable, caught up in the ravages of the First World War. At one birthday party, he remembered machine-gun fire strafing his grandparent's home while everyone hugged the floor in panic. This was the first of many 'I've almost been killed' episodes which were to punctuate Heinz's life. The Löwenstamm family was hit hard by the German economic depression in the 1920s and the hyperinflation that followed. Due to his interest in the natural sciences, and with the encouragement and support of his maternal grandfather, Heinz entered what was then an experimental *Höhschule* focused on math, physics, and chemistry as major subjects (in contrast to the *Gymnasium*, which provided a more academic education focused on the classics). Heinz found his new school area more conducive for collecting fossils than minerals, so he swapped collections with one of his teachers who wanted to become a mineralogist; that's when he started his first systematic fossil collection and

gained the desire to be a paleontologist. A seminar in his town given by Alfred Wegener – who first proposed the continental drift theory – expanded his interest to include geology, not just paleontology.

With continued support from his grandfather and his uncle Nindseil, Heinz was able to enroll in the vertebrate paleontology program at the University of Frankfurt. However, their leading paleontologist died suddenly just prior to his arrival and the entire program collapsed. The students scattered to other universities, and in the fall of '33 Heinz chose to continue at the University of Munich, which had the strongest overall German program in paleontology with the most international outlook. Shortly thereafter, Adolf Hitler was named chancellor and the situation for German Jews became increasingly more precarious. Unfortunately, some of the professors at Munich were influenced strongly by Nazi propaganda. Others, such as Heinz's mentors Prof. Broili and Edgar Dacqué, were willing and able to ignore the rhetoric to some extent. About this time Heinz met his future first wife, Ilse Weil, a student in the Ludwig-Maximillan University Medical School, at a vegetarian restaurant.

This Nazi influence resulted in a most unusual twist in Heinz's choice for a Ph.D. thesis topic. During a student field trip early in 1935, Heinz recalled one of the Nazi-influenced professors (Kölbl) pounding the table and saying, "*German things must be done by Germans*". A few minutes later, he had the tenacity to ask Heinz what he was planning to for his Ph.D. dissertation. In a fit of sheer impulsive rebellion, Heinz announced that he was going to work on the geology of Palestine, despite the fact that he had absolutely no personal resources to do so! Depressed at having shot his mouth off, he mentioned this to his friend and landlord later that evening, who said, "*Don't worry – I have friends in New York. They will take care of it!*" Unbeknownst to Heinz, these friends

were financed by the Iraq petroleum company that was very interested in the geology of the Middle East, and were eager to have good geological and paleontological studies done in the area.

So Heinz went to Palestine for 18 months. Although the area was still a British protectorate, Heinz realized that he would need to cooperate with the Bedouins to have full access to his field area. With a proper introduction from the British district commissioner, he was able to live with the family of the Number One Sheik for several months, learning Bedouin Arabic in the process. During the introduction, however, Heinz was forced to smoke for his first time; refusal would have been a deadly insult to the sheik and his family. (That led unfortunately to a 45-year tobacco addiction and his ultimate demise from lung cancer.) During his 18 months in Palestine, Heinz was able to complete the first geological and paleontological analysis of the Eastern Nazareth Mountains, which turned out to be one of the critical areas for understanding the geology of the entire Dead Sea rift system. During this time, geologists from the Iraq Petroleum Company utilized his geological and paleontological skills, as Heinz was invited repeatedly to participate in field excursions throughout the entire Middle East. All they asked for in exchange for these trips was to have copies of his field notes. At the time, Heinz did not know that this was also the ultimate source of his field support in Palestine.

Upon completion of his dissertation research in the middle of 1936, Heinz returned to Munich and spent about a year finishing his thesis. After it was accepted, and the date for his exam was scheduled, he and his fiancée (Ilse) were married. One week before his thesis defense, however, the Nazi government issued an edict that no more Jews would be allowed to receive their Doctor degrees at German Universities. They were out in the cold, with nothing to show for their

many years of university education. Heinz was left without even a bachelor's degree (the German Ph.D. was an all-or-nothing affair). They had no options but to leave. Several of the geology faculty at Munich then did an extraordinarily risky thing, as noted by Heinz.

So Dacqué wrote a letter on official university stationery, with the Nazi university seal on it, saying I had fulfilled the qualifications of the Ph.D., but due to political circumstances, they couldn't give me the diploma. He went over with me to Broili who was the head of the paleontology department to have Broili sign where he had typed out his name. Broili sat down and signed. Within ten minutes, Kölbl [the Nazi professor] asked me to see him. I came in, and said, "I would like to see the letter which you just got from Broili and Dacqué". I said, "What Letter?" He said, "Don't be silly". He went over to my pockets and he knew in which pocket I had it. He pulled it out, read it; his eyes popped out, he got mad. He gave it back to me and said, "Nice letter, isn't it." He knew I was going to leave within a week or two. I said, "Yes". He said, "I want to give you a letter of recommendation, too. But you must not show it to the *Chicago Tribune*, because you know what would happen to me if you did that." I said, "I don't want your recommendation." He didn't listen. He sat down and wrote the letter – I was a good student, in general terms – and gave it to me. As I went out the door, he said to me, "You cannot go to America and say that we mistreated you, can you?"

Fortunately, Heinz and his wife had managed to get visas to immigrate to the United States, being sponsored by his wife's uncle in Chicago. The major problem was that the American government considered Heinz to be a Polish citizen, given that his birthplace, Upper Silesia, was then part of Poland. (Heinz was a German citizen and had never been in Poland, yet they told him he was Polish!) The visa queue for Polish citizens seeking to immigrate to the US had been hopelessly overdrawn for 15 years. However, the American consul in Stuttgart – the closest one – gave him one of three emergency visas; Heinz later came to suspect that it was the silent efforts of the oil company that had financed his studies in the Middle East that made this arrangement possible.

Heinz's parents and sister also managed to escape to Brazil, but many of their other relatives later perished in the Holocaust.

Upon their penniless arrival in Chicago in June of 1937, Heinz discussed his situation with several of the geology faculty at the University. At first they simply looked through his grade sheets with little apparent interest, until someone noticed the letter from Broili and Dacqué. As Heinz recalled in his oral history transcripts,

I hadn't thought of it. The letter happened to be in my pile of papers. They saw that letter and said, "Could we open it?" They read it, and – I'll never forget – their eyes got big. "Broili, Dacqué, they recommended?" After that, the whole atmosphere changed dramatically. I immediately got a scholarship, in the middle of the year. I was told I would have to take a few courses, translate my thesis, and within a year or two I could get my degree. That's when I realized how important that letter was. It was a miracle that Broili and Dacqué had done it, too, because without it, I don't know."

After only a minor setback for failing his German Language test, Heinz finally received his Ph.D. from the University of Chicago in 1939.

In one aspect, Heinz was frustrated with his experience in Chicago. Having fled from persecution in Germany amid the destruction of his friends and family, his main goal was to enlist in the American army so that he could go and fight the Nazis. When America finally joined the war, he was listed initially as an 'Enemy Alien', and subjected to severe travel restrictions, even to the extent of having his camera confiscated. When the Arctic and Desert Division of the Army realized that they could use Heinz's familiarity with the Middle East for their campaign in Egypt, they lifted his enemy status and rushed his citizenship papers through in record time. However, before he could go the battle in Egypt was over. At that time, the German U-boats were sinking the oil tankers going from Texas to the East coast, and the military argued

correctly that he would be of more use to them as a civilian working on the coal and oil reserves for the Illinois Geological Survey. Still, Heinz managed to help the war effort by interpreting aerial photographs of the Ruhr district coal mines for the Army Air Core, and recognized that modifications to the coking ovens were designed to extract high-octane aviation fuel. The Allies bombed the plants, putting them out of business and giving Heinz some measure of revenge.

For a short while after graduation, Heinz worked for a small oil company, and then moved to the Illinois State Museum as a curator of invertebrate paleontology. Having no funds for field research, Heinz discovered that he could take the Chicago streetcar system to the end of the Stony Island line, reaching an area rich with fossil coral reefs. His rationale for launching his studies on the paleoecology of the coral reef environments (which led eventually to the recovery of enormous quantities of oil) is best expressed in his own words from the Caltech archives:

It was called Stony Island because there were fossil reefs cropping out – coral reefs. I went over there, and it was in terrible shape. Then, I discovered next to it, long dump piles that had been made when drainage canals were built to connect the Illinois River with the Great Lakes to get barges through. In digging the canals, the work crews had dumped all this stuff on the side. I started to walk over those old dump piles, and I found very nice fossils, all marine, and I knew they were from the Silurian period – about 400 million years ago. Some people from the Field Museum had already catalogued some of these fossils – the black shale type... but nobody had looked at the skeletal remains in dolomite. I made a big collection of the material over a period of time and then tried to identify it. I couldn't. I researched the local literature, and none of the fossil groups that had been described from the Chicago area fit what I had found at all."

As Heinz expended his attempts to identify the fossils, he eventually discovered that they matched almost precisely Silurian fossils described from Tennessee. Previous paleontologists who had studied the fossils from museum drawers

had assumed that the two populations were from two geographically separate areas, one in the South and the other in the North, but Heinz had found them in the same area. The Northern population was in fact composed of organisms that lived in the reef environment, in the active wave zone. The Southern fauna simply lived in deeper waters, and was composed of smaller forms adapted to a darker, less active environment. Upon further study, Heinz discovered that he could identify changes in the ecological communities surrounding the reef environments that varied systematically with distance from the reef complex, and was even able to determine the direction of the prevailing winds 400 million years ago from the horseshoe-shape atoll structures. By examining subsurface cores from several localities, he was able to use these distance estimates to determine the location of buried fossil reefs. Ultimately, Heinz discovered a massive system of Silurian reefs that stretched from the edge of the Ozark Mountains to Greenland; it had been larger and more magnificent in Silurian time than the Great Barrier Reef of Australia is today.

Heinz also realized that the porous structure of a buried reef complex was an ideal trap for oil and gas. Several major companies had discovered oil in the Chicago area almost by random drilling, and Heinz's ability to pinpoint the locations by simply examining the cores seemed nearly miraculous. Two of the companies even went so far as to break into Heinz's office, looking for information on where to drill; Heinz was able to identify the bandits by marking fake locations on his office map and watching which company started drilling there. Despite financial offers of up to 1 percent of the profits for the proprietary use of his technique (which would have made him a *very* wealthy man), Heinz instead chose to publish his findings in the open scientific literature for the benefit of all. His only compensation was the gift of a

binocular dissecting microscope from one of the companies. However, the title of his 1948 book on the topic (Biostratigraphic studies of the Niagaran inter-reef formations in north-eastern Illinois, published by the Illinois state museum) was so obtuse that it triggered a local columnist for the Chicago Tribune to complain in print about the waste of state funds on such useless studies. This triggered a heated public response from the presidents of several major oil companies, who noted that the work was leading to the recovery of enormous volumes of oil. His monograph was republished many times by the oil industry.

Immediately after the war, the University of Chicago was the hotbed of isotopic research, and was in particular the birthplace of isotope geochemistry. Harold Urey had recognized the importance of isotopic measurements for interpreting the past history of the Earth, and had assembled a team focused on using deviations in stable isotope ratios to measure the temperature of ancient oceans. Urey had obtained fossils of Mississippian age (about 300 Myr old), extracted the calcite from the shells, and had determined a temperature of about 60°C – higher than any known animal was able tolerate! One of Urey's colleagues recommended that he consult with Heinz about the plausibility of this result. After looking at thin sections of the fossil materials, and comparing them to living relatives, Heinz pointed out that the shells had been recrystallized completely. They had measured the temperature of the hydrothermal fluids that had altered the fossils, rather than the temperature of the oceans in which the animals had lived. In his studies of the ecology of fossil reefs, Heinz had been interested particularly in the variability of fossil preservation, and had started a special collection of fossils that had been unusually well preserved. These provided much better materials for isotopic study, and gave much more reasonable paleotemperature results. Urey was

estatic! Heinz was a gold mine of materials and ideas, and his expertise was needed urgently by their paleotemperature research project. Two months after his first meeting with Urey, and after much arm-twisting, Heinz left the Illinois Geological Survey and accepted a position as a 'Research Associate in Geochemistry' at the University of Chicago. The title was rather peculiar for those days, and he was often referred to informally as Urey's "Atomic Paleontologist". After another year, and with much more arm-twisting, Urey convinced Heinz (and the Chicago Administration) that he should also teach as well as doing research, as it was the best method to attract the best, most skilled students. Heinz at first thought that his horrible blend of 'Milwaukee-German/English' would preclude effective teaching, but in fact it enhanced his rapport with the students.

From his position with the Urey group, Heinz was able to continue his research on Silurian reefs as well as to extend his search for pristine fossil shell materials; an interest that later paved the way for his studies on biomineralization. One of the most exciting geochemical results ever came from their study of upper Cretaceous cuttlefish which had annual growth rings preserved in an unaltered carbonate matrix - isotope paleotemperatures clearly showed the amplitude of the seasonal warming and cooling cycles experienced by animals that lived in the oceans 80 million years ago (Urey, Epstein et al. 1951). It was an intellectual milestone – the first direct and quantitative measurement of an ancient climate signal.

One of the amusing legends of the Chicago years was the progressive change in Heinz's office over the 4-year period (related by his colleague, Sam Epstein). There was initially a straight, uncluttered path from the door to Heinz's desk. Gradually with time this evolved into a more winding path, as piles of wooden drawers with fossils, maps, journals, notes, and glass sample vials filled with mysterious powders accu-

mulated along the route. Eventually, his desk disappeared from view, and one had to tread carefully through the maze to avoid upsetting things. Finally, one day Sam noticed a small note on the outside of the door, stating that Heinz had moved his desk to the empty room room next door!

Between 1950 and 1952, members of the Urey geochemistry group migrated largely to California, both to Caltech and the University of California, forming the core of new isotope geochemistry programs.

Initially, Heinz was hesitant to leave Chicago, but it was clear that most of the young, exciting geochemists of the Chicago mafia were departing; and even Urey eventually moved to California. Harrison Brown, Sam Epstein, and Clair Patterson came initially to Caltech and founded a new program in Geochemistry; with support from the AEC this group was able to attract a superb engineer (Charles McKinney) to build the mass-spectrometers. Heinz himself was not an 'Instrument' person, but he knew intuitively which measurements were significant and which analytical standards were important (such as his Pee Dee Formation Belemnite sample, now known as the PDB standard for carbon isotopic analyses). It was clear that Caltech was on the right track, and with encouragement from his principle collaborators he eventually agreed to move West. When the Chairman, Bob Sharp, asked him what his professorial title should be, Heinz replied, a 'Paleoecologist'. When asked what that discipline involved, Heinz would usually state that it was 'professional beach-combing', or whatever he happened to be interested in at the time. Although he continued his collaborations with former members of the Urey group – particularly Sam Epstein – Heinz became ever more interested in the processes through which various living organisms use to control their mineral hard parts. Initially, these studies were driven by the necessity of having 'ground truth' for the study of fossil materials –

if the paleotemperature measurements did not work on a modern clam, grown in open ocean waters of known temperature, how then could one interpret results of ancient, fossil materials? Similarly, he was interested in developing geochemical methods that could be used to obtain other important information about ancient ecosystems, such as salinity and barometric pressure. These problems led him to study the environments of modern reef systems, particularly those in Bermuda and Palau, which had long-term oceanographic records of temperature and salinity, and for which collection of materials of various depths was relatively easy.

As an early recipient of support from the Office of Naval Research, Heinz was allowed to travel freely through the Pacific using the military air transportation system in the 1950s. Caltech and JPL had played a leading educational and research role in the war effort, and apparently some bureaucrat back then had decided that a Caltech Professor had the rank equivalent to an Admiral, so Heinz and his assistants were treated royally. When he realized how the military bureaucracy worked, Heinz exploited the system to gain access to remote areas, and did not hesitate to request the military boys to do reconnaissance aerial photographic surveys over areas of special ecological and geological interest. As always, he was a dedicated naturalist, and managed to survive and flourish despite extreme conditions in the field. One of the amusing legends of Heinz during this time concerns his attempt to extract a particularly interesting organism from the reef front in Palau while snorkeling. The small motorboat with his Palauan driver and assistant were nearby when they noticed a large shark swimming rapidly towards them. Despite their shouted warning, Heinz refused to stop hammering away at the reef. As his crew started to panic, and as the shark closed in for the kill, Heinz turned around precisely on time and smacked the animal firmly on its snout with the flat

end of his rock hammer. Dazed, and with most of its sensory organs out of commission, the animal wandered away and let Heinz return to his work.

As most of the biomineral products produced by reef organisms were forms of CaCO_3 (the minerals calcite, aragonite, and more rarely, vaterite), Heinz focused most of his research activities during the 1950's on them. Among other things, he discovered that the aragonite needles which form most of the sedimentary mass in the back-reef lagoons of Bermuda were actually produced by microscopic algae; this triggered a vigorous debate with carbonate petrologists, all of whom had assumed that they formed through inorganic processes. The carbon and oxygen isotopes, however, convincingly pointed towards the biological origin.

Heinz's discovery of magnetite biomineralization is a premiere example of how a good eye and a keen mind can lead to important discoveries, even today. The story begins in 1961 when he was sitting at low tide on a wave-cut platform in Bermuda, and began to wonder how the erosional processes had produced such a level, almost beveled-off substrate. He had seen similar benches in Palau, where the limestone had eroded into hundreds of 'nip islands', each resembling a large mushroom with waves splashing around the base and dense vegetation on top. At the time, the dogma was that these were wave-cut benches, perhaps with some help from salt crystal formation at low tide. For some reason this did not satisfy Heinz, who took out a hand lens and examined the limestone substrate more closely. Surprisingly, the surface was covered with long strips of small chevron-shaped groves that wandered over each other and overlapped in complex patterns, something like tangled noodles. While he was examining this, a chiton (a mollusk of the class Polyplacophora) wandered by, leaving a fresh noodle trail like this chiseled into the rock surface! Heinz realized immediately that the

chiton was scraping off the outer (somewhat greenish) layer of the rock surface, feeding on endolithic algae growing in small cracks in the limestone. But for this to be the case, the animal's teeth needed to be harder than the limestone substrate it was feeding on. The biological dogma at the time held that the teeth of mollusks were made of a proteinaceous material like fingernails, which would not have been nearly hard enough to use as a rock chisel. A quick dissection revealed that the teeth along the animal's tongue plate (the radula) were black and very hard, obviously mineralized with *something*, but clearly not calcium carbonate or a calcium phosphate mineral like apatite (such as in human bones and teeth). The black tooth mineral was present in every individual and every chiton species he examined. Tooth shape was even species specific, some having several prongs and others curved, cup-like structures.

Determining just *what* the hard, black stuff was proved to be more difficult. Back in the early 1960s, the best analytical tool for precise mineral determination was X-ray diffraction, and the standard technique was to use a narrow beam of Cu-K α radiation. However, when the chiton teeth were measured in this fashion the photographic emulsion came out completely fogged. The technician operating the instrument, Art Chodos, suggested that it might be some interference or fluorescence, and recommended changing the X-ray source from Cu to a different metal like Ni or Co. That eliminated the interference problem, and produced a nice set of diffraction lines. Unfortunately, they did not match any of the standard minerals that are commonly found in the reef environments. Stumped, Heinz and his assistant decided to search methodically through each mineral in the standard diffraction compilation until they found something that matched. After several days of searching, pure magnetite (Fe₃O₄) popped up suddenly as a perfect match! Intrigued, Heinz then took a

small hand magnet and discovered to his amazement that the entire radula stuck to it as strongly as if it were a nail – it was obviously ferromagnetic. Subsequent chemical analyses confirmed that iron was the main component in the teeth; it also explained the problem with the X-rays, as the Cu-K α line causes iron to fluoresce, fogging the film.

It is important to put this discovery into the proper historical perspective. In 1961, magnetite was known to be a dense, inverse-spinel mineral that formed exclusively in high-temperature, high-pressure igneous or metamorphic environments. It was thought to be terribly out of equilibrium at room temperature and pressure, and was simply not something that could be produced in the mouth of a mollusk! Mineralogists and petrologists assured Heinz that the chitons had to be picking up grains of magnetite from the sand, in the same way that sharks and rays were known to accumulate heavy minerals in their inner ear for their balance organs. But by simply dissecting out the radula and looking at it carefully, Heinz was able to show that the iron was of biological origin. It accumulated first as the iron protein, ferritin, in epithelial cells that were tightly attached to a proteinaceous but unmineralized embryonic tooth. The iron was then transported rapidly into the young teeth in the form of the mineral ferrihydrite (hydrous Fe₂O₃), forming a few rows of bright red teeth. At a very sharp, sudden transition most of the tooth volume was converted into black magnetite, with gradual addition of more ferrihydrite (converting to magnetite) as the teeth matured. This simple series of observations was able to shut up the most severe critics instantly. Magnetite *was* being formed at low temperatures and pressures, in an animal, no less! Although it is now well known that magnetite can be precipitated from aqueous solution under strongly reducing conditions, it was not appreciated in 1961.

Of additional importance was the fact that the radular teeth stuck strongly to a magnet – that was the first clear, macroscopic and easily reproducible effect of a magnetic field on a biological structure, and in one sense earns Heinz the title of ‘Father of Biomagnetism’. (This was actually a much simpler biomagnetic effect than Linus Pauling’s 1933 discovery that deoxyhemoglobin is paramagnetic.) In his seminal 1962 paper reporting this discovery, Heinz noted that chitons were known to have a local homing instinct, with individuals returning to their own preferred depressions in the rock during low tide. Interestingly enough, he did not suggest explicitly in that paper that they might be using a magnetite-based compass as a navigational aid, but it is clearly implied from the context! It is a pity that the paper was published in the *Bulletin of the Geological Society of America*, because not many biologists read it. Numerous claims of apparent magnetic field sensitivity in animals had been made prior to 1960. Biophysicists, however, were vociferous in denouncing those studies for the simple reason that they knew of no plausible mechanism through which the weak magnetic field of the Earth could influence the diamagnetic and paramagnetic materials present in living organisms, and magnetic induction was too weak to be of use via an electrical detection system. Prominent neurobiologists had even stated flatly in print that there ‘were no physiological ferromagnetic materials’, and hence magnetoreception was impossible. Heinz’s discovery of magnetite in the chiton teeth obviously undermined the basis of this biophysical argument (and paved the road for much of *my* research). Subsequent discoveries have confirmed the central role of magnetite as the biophysical transducer of the magnetic field in living organisms spanning the evolutionary spectrum from the magnetotactic bacteria to mammals, with a fossil record extending at least 2 billion years back on Earth, and perhaps 4 byr on Mars. (As of this

writing, the best evidence for ancient life on Mars is the presence of probable biogenic magnetite in the ALH84001 meteorite.) In the vertebrates, chains of uniformly-sized magnetite crystals, optimized for their magnetic properties, have been found recently in specialized cells connected to the ophthalmic branch of the trigeminal nerve; this nerve is now known as the main conduit of magnetic field information to the brain. This magnetite-based system is one of the few truly novel sensory modalities discovered in the past 50 years, and Lowenstam's discovery in the chiton teeth was the first hint that anything like this might be possible.

Rather than pursue the neurophysical aspects of the magnetite discovery, Heinz wondered what other weird minerals living organisms might form. Within a few months, he discovered goethite (γ -FeOOH) capping the teeth in another primitive group of mollusks, the Archaeogastropods. During the 1960's and 1970's, the mineral list grew steadily beyond apatite, carbonates, and opal to include lepidocrocite, vaterite, ferrihydrite, weddellite, dahllite, and a variety of amorphous iron and phosphate minerals, to name a few. In addition, Heinz began a systematic compilation of the phyletic distribution of these materials, as well as efforts to track the time of their evolutionary origin. In this process, he made another fundamental observation concerning the biological processes that different organisms used to form biominerals – there was a clear spectrum of biological control. Some organisms actively direct every aspect of the mineral formation process, including chemical purity, crystallinity, crystal orientation, crystal shape and size. By precipitating the minerals inside the cell, they produce mineral products that are unlike anything produced inorganically. Due to the complex assemblage of biomolecules involved in this type of mineralization, Heinz termed this process 'matrix mediated' or 'biologically controlled' biomineralization. On the other hand, some min-

erals simply form as an indirect result of biological activity, associated with metabolic byproducts; these he termed 'biologically induced'. By standing back and looking both at the temporal distribution of fossil forms, and their phyletic distribution, Heinz was able to observe new patterns in the data relating to the underlying biochemistry. Of particular importance was his observation that virtually all of the mineral products which appeared nearly simultaneously in the Early Cambrian (the Precambrian-Cambrian boundary interval) in approximately 40 phyletic-level groups involved the use of calcium minerals (phosphates and carbonates). In a seminal paper co-authored with Lynn Margulis in 1980, he noted that all of the requisite biochemical transport systems for this process had to have been present in the last common ancestor of all animals, as all eukaryotic cells rely on the precise control of calcium ion concentrations to regulate the mitotic processes (via microtubule polymerization), and for second-messenger systems. Hence, most of the difficult 'evolutionary prerequisites' needed for the widespread biomineralization of evolving animal groups were already present long before something associated with the Cambrian Explosion (like a runaway predator/prey interaction) triggered the biomineralization cascade. This concept certainly is the foundation of a 'Grand Unified Theory' of biomineralization, which may help to unravel the complex genetics and biochemistry of biomedically important processes like tooth and bone formation.

Despite the pain and the suffering that Heinz experienced as a youth in Germany, California life and 'professional beachcombing' calmed him. For many years after World War II, he had severe aversions to all things German, including a sincere inability to speak the language and a strict injunction against traveling there. How could he? German citizens in his age group bore responsibility for the Holocaust

that destroyed his family, despite the fact that his ancestors had lived in Germany for at least the previous 400 years. Those of us who knew Heinz well were therefore stunned when the Faculty in Munich presented Heinz with an honorary Ph.D. in 1980, *and he accepted it!* This apparently took several years of careful, advance preparation by Lynn Margulis, Dolf Seilacher, and Wolfgang Krombichner, who gradually managed to persuade Heinz that it would be a good signal to the younger German scientists who bore no responsibility for the errors of their parents. Even so, Heinz remembered the experience as troubling, particularly when he saw elderly Germans catching the bus in Munich and wondering "what were they doing during the war -- were they responsible?".

To Heinz's academic children, he was a quiet intellectual giant who spoke with a soft Milwaukee-German accent, which for many years was muffled severely by the use of cigarettes. During class lectures we had to sit quietly near the front simply to hear him – but no one ever complained, as he was a stimulating and fascinating lecturer. In one episode in the early 1970's we counted no less than 5 lit cigarettes at the same time scattered along the chalk tray, as Heinz would become so excited and immersed in his subject that he would forget that he had already had some lit. Even on his field trips – particularly those memorable excursions to Baja California shared with Leon T. Silver – Heinz would grab our attention for hours on end, and amaze us with his ability to see subtle relationships between form, function, chemistry, and biology of natural and ancient ecosystems. In the evenings around the campfire under the protection of beautiful groves of California Oak trees, he would tell us endless stories of the South Pacific, Palau, Japan, South America, and his childhood in a fractured and war-torn Europe. We at first thought most of these were fairy tales, until various friends and colleagues, former students, and family confirmed them later.

Heinz inspired all of us to pursue our own intellectual interests wherever they would lead, with total disregard for personal fame, fortune, or personal safety. We miss him dearly.

Heinz shared his life with 3 talented and caring women, 3 gifted children, many grandchildren, and many more academic offspring, including the present author.

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