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Introduction

"Potres." One of my earliest childhood memories is that of my mother uttering this word in disbelief. Quake. I recall the sudden awakening, my mother's comforting embrace, and the prolonged clinking of the shaking glasses and porcelain in the living room display cabinet on the second floor of our three-story building.

My childhood was peaceful, spent in the small provincial town of Vinkovci in Croatia, nestled in the southern part of the Pannonian Plain. Known as one of Europe's oldest continuously inhabited settlements, with a history stretching back 8,000 years, Vinkovci seemed an unlikely backdrop for anything more dramatic than snow flurries, let alone something as astonishing as an earthquake. At the time, my understanding of earthquakes came from fleeting images of devastation and tragedy occurring in distant corners of the globe, pictures which occasionally flickered across our bulky television screen. In those days, such events seemed worlds away, mere curiosities far removed from the quiet rhythms of my everyday life. But that evening, it was indeed a quake that disrupted the calm.

A deep, ominous rumble, followed by an intense vibration, snapped me out of my thoughts. My tiny, wooden house in

Berkeley, California, perched precariously close to the Hayward Fault, shuddered so violently that I felt goosebumps and an uncomfortable thrill. I was experiencing another earthquake, feeling its waves ripple through me. A fascination with seismology, the science dedicated to understanding earthquakes and the waves they generate, had led me from my comparatively quiet birthplace in Europe to pursue a PhD and postdoctoral research on the west coast of the American continent, where the Earth's movements are more than just distant or rarified curiosities—they are a tangible and ever-present reality. After an initial sense of shock, I was filled with an inexplicable joy.

My ongoing research into earthquakes eventually led me yet another ocean away—to a small, top-floor flat in a Yokohama suburb, where I worked on a book I had started writing on the Earth's inner core. A small table squeezed between the bed and the wall had space for little more than my laptop, a notebook, and a pen. As evening descended, my thoughts drifted beyond the blooming cherry trees, across the harbor, and back over the vast expanse of the Pacific to where I had spent my doctoral days in the San Francisco Bay Area. Almost as though the Earth was responding to my thoughts, I felt a local quake stir, its tremors shaking the flat. It felt like some slumbering giant awakening briefly, pulling my thoughts back to the earth beneath my feet.

If not for my fascination with such stirring giants and the powerful waves they send through the planet's interior, I never would have traveled so far around the world—lastly, to the smallest of all continents, Australia. Here in Canberra, I work as a seismologist, studying quakes to better understand the inner workings of the Earth and other planets. In March 2020, my sister texted me from her home in Zagreb, the city of my student days, where a quake measuring 5.5 of Richter magnitude had struck. Like many residents of Zagreb and its surroundings, she was deeply affected by the quake, and the days that followed were filled with unease and anxiety—compounded by the fact that the city was in lockdown due to the coronavirus pandemic. From halfway around the world, I answered her—and then went on to engage in many online conversations about earthquakes with residents of Croatia, who were seeking to make sense of their experiences. When another, even more powerful earthquake struck late that same year near the town of Petrinja, not far from Zagreb, my writing began to evolve, and I decided to write a popular-level book. I felt a duty to clarify the phenomenon of earthquakes and explain the sensations caused by passing seismic waves in a deeper and more expansive way than short social media posts allow.

I originally published the book you are now reading in my native language of Croatia, but the global perspective I have gained through my travels eventually compelled me to translate the book into English in order to share a scientific understanding of earthquakes and the Earth's interior with more people. Inspired by my childhood memory of the quake that my mother and I experienced, as well as the experience of explaining earthquakes to Croatian people on social media after my sister texted me from Zagreb, I decided to use the two earthquakes that occurred in 2020 in Croatia as examples later in this book. While earthquakes are far more infrequent in the tiny European nation where I grew up than in places like Japan or California, the very nature of global seismology transcends the borders of any one country, and these two earthquakes provided an opportunity for me to explain both the personal sensation of an earthquake and some of its fundamental characteristics. I have made slight adaptations for readers who may not be familiar with Croatia and its surroundings.

Overall, the book is designed as a standalone read that, I hope, will captivate anyone curious about the science of earthquakes and the mysteries of the Earth's interior, as well as people who have experienced personal encounters with earthquakes. The book is also suitable for high school students or university students in the early stages of studying seismology. Organized into ten chapters, the book explores the history of seismology and the nature of earthquakes but also shares more personal reflections and experiences from my life as an observational seismologist. My work has brought me to some fascinating (and challenging) places—and so our quest to reveal the secrets of the Earth takes us from Eurasia and North America to the remote corners of the Australian continent, down into the icy waters of the Southern Ocean, and even beyond, to the desolate landscapes of the Moon and Mars.

In chapter 1, I place Earth within the broader context of the Solar System and the universe, examining it as a planet whose surface activity directly results from its internal dynamics. Here, we step into the realm of planetary physical processes: the formation of planets, the stratification of their interiors, the crystallization of the inner core, the phenomenon of the geodynamo, the generation of the geomagnetic field, mantle convection, plate tectonics, and the earthquakes and volcanoes that arise as a consequence of our planet's inner workings. Earthquakes are not merely disruptive events; they are witnesses to the planet's evolution and internal dynamics, messengers from the depths of time reminding us of the ceaseless activity beneath our feet. They are, in a sense, travelers through time, carrying with them the story of our planet's ongoing journey.

Chapter 2 delves into the rich tapestry of Earth science history, uncovering fascinating details about our evolving understanding of earthquakes. It begins with an ancient tale, the

Japanese legend of Namazu, the giant catfish believed to cause seismic disturbances. The narrative then moves to the late 19th century, when John Milne's invention of the first seismograph marked a significant milestone in earthquake study. The chapter climaxes with the San Francisco Earthquake and Fire of 1906, a devastating event that shifted our perception of earthquakes. It was this disaster that unveiled the true nature of earthquakes as originating from fault zones where rocks are poised to break under accumulated tension. Amid the devastation, an unusual footnote to history was written: a cow named Matilda, tragically caught in the quake, fell into a fissure along the San Andreas Fault. Her predicament made headlines, symbolizing the unexpected consequences of the event. Before this, it was widely believed that faults were the result of earthquakes rather than their cause. The San Francisco Earthquake and Fire not only redefined our understanding of earthquake mechanics but also revolutionized our view of Earth as a dynamic, active planet. This seismic event gave impetus to the rapid growth of a new geophysical discipline—seismology, a burgeoning discipline at the time—and laid the groundwork for the hypothesis and eventual theory of plate tectonics, forever altering our comprehension of the Earth's internal processes and its ever evolving nature.

Chapter 3 brings to light the monumental discoveries of the pioneers who reshaped our understanding of the Earth's interior: Andrija Mohorovičić and Inge Lehmann. While Milne laid the groundwork for modern seismology by building a seismometer, Mohorovičić and Lehmann further illuminated the Earth's hidden depths. Andrija Mohorovičić, a seismologist and meteorologist, made groundbreaking strides with his discovery of the Mohorovičić Discontinuity, or "Moho," which revealed the boundary between the Earth's crust and the underlying mantle. This revelation was a pivotal moment, offering new insights into the Earth's structure and laying the foundation for future research. A little later, Inge Lehmann advanced our knowledge even further by identifying the existence of the Earth's inner core, a discovery that transformed our understanding of the planet's internal workings. Her work built upon the discoveries of her predecessors, providing a clearer picture of the Earth's layered structure. These trailblazers did not look to the skies but instead turned their gaze downward, sliding along the verticals into the depths of our planet. Their discoveries have inspired countless Earth scientists, including myself and my colleagues, who stand on the shoulders of these giants. Their monumental contributions continue to influence and guide the field of seismology, shaping our understanding of the Earth's interior and the dynamic forces that drive its processes.

The central narratives of chapters 4 and 5 revolve around the seismic giants that stirred continental Croatia and surrounding countries in 2020—the earthquakes near the city of Zagreb and the neighboring town of Petrinja. Though seemingly unrelated, these two events occurred within the same calendar year and shook the entirety of central Europe. They serve as examples for exploring how seismologists analyze ground motion records—that is, by using seismograms to pinpoint the location and magnitude of earthquakes. The chapters delve into the scenario of these earthquakes, providing a comprehensive look at how seismologists use their tools to decode the quakes.

We journey from the earthquake's epicenter, on the crests and troughs of these waves, through the intricate workings of the Earth's layers, to the sensitive seismographs that measure ground movement. Eyewitness accounts shared on social media offer palpable illustrations of the sensations experienced in different locations and times, capturing the sound and senses of ground motion during and after the quakes. Through these accounts, we explore fundamental concepts such as the differences in earthquake magnitude, the frequency of aftershocks, the triangulation method, and the use of spectrograms and geodetic interferograms. We also discuss the nature of sound and infrasound during earthquakes and whether and how earthquakes may be temporally and spatially connected. These chapters lay the foundation for a deeper exploration of earthquake forecasting and possible prediction discussed in subsequent book sections.

From the warmth of southeast Europe, we journey to a cold, star-studded winter night over the Barents Sea, where the aurora borealis dances in shimmering waves across the upper reaches of the atmosphere. Beneath the frozen expanse of the Kola Peninsula, we find ourselves at the site of humanity's deepest borehole—a monumental feat in our quest to probe the Earth's interior. Yet, despite the impressive depth we have achieved compared with the deepest mines, it becomes clear that we have barely "scratched the surface" in our journey toward the Earth's center.

In chapter 6, we linger a bit longer with the theme of earthquakes but with a new focus. Here, modern techniques of seismogram analysis come to the forefront, revealing how we use these seismic waves to "image" the Earth's internal structure. Although earthquakes are not the primary subject of study here, they serve as the source of waves that traverse the Earth's surface and penetrate its depths. When direct exploration is constrained by the extreme temperatures and pressures of the Earth's crust and mantle, we rely on seismic waves to guide us. This chapter introduces seismic tomography, drawing parallels with medical tomography to explain how it maps the Earth's internal structure. I describe the insights we have gained about the Earth's interior, though the image remains somewhat blurry. However, our picture is becoming increasingly sharper thanks to recent and ongoing advancements, offering us a more defined glimpse into the mysteries beneath our feet.

Chapter 7 ventures into the heart of one of science's most tantalizing questions: can we predict earthquakes, and is there hope for accurate predictions in the future? The chapter opens with an account of the 1976 Tangshan earthquake—a disaster that left an indelible mark on the Chinese city and became one of the most devastating seismic events in recent history. This heart-wrenching story sets the stage for a broader exploration into the world of earthquake prediction. Our journey then takes us deeper into China's seismic history, where I examine other significant earthquakes and early prediction attempts. The tale of the Haicheng earthquake stands out, where a rare success in forecasting ignited excitement and methodical approaches to predicting quakes. Yet, the optimism that once surrounded earthquake prediction was met with harsh reality. As the devastating impacts of Tangshan taught us, predicting earthquakes proved far more complex than anticipated, leading us to reassess our methods.

With a renewed focus on scientific methods, the chapter shifts to Parkfield, California. Here, I reflect on how the pursuit of earthquake prediction has evolved, marking a return to understanding fault processes and seismic behavior. I conclude by examining modern research directions—a metaphorical "crystal ball" of contemporary science. Through this lens, I explore the innovative strides being made and the ongoing quest to unlock earthquake prediction. As we look to the future, the hope of accurately predicting earthquakes remains a compelling and elusive challenge, driving the relentless pursuit of scientific discovery.

In chapter 8, we are immersed in the fiery expanse of the Australian Outback, in the rich redness of its ancient rocks, the mystique of Aboriginal heritage, and exotic wildlife. As we traverse Stuart Highway and other remote parts of the continent, we find ourselves in a natural laboratory unlike any other. Amid this rugged landscape, we delve into the intriguing world of nuclear testing and the global efforts to detect and prevent clandestine nuclear experiments. I will take you to Warramunga Seismic and Infrasound Facility, a critical observatory nestled in the heart of Australia's iconic Red Centre, with which I have an inseparable connection. This outpost stands as a sentinel, monitoring seismic activity and contributing to global efforts to ensure compliance with nuclear test bans. Through this chapter, I explore the importance of uniform spatial coverage by seismographs and why even the most remote and uninhabited places are vital for global seismology. As we navigate the harsh beauty of the Outback and its role in our understanding of seismic phenomena, we uncover the essential contributions of these isolated regions to the broader field of Earth science.

In chapter 9, we venture into the heart of a geophysical expedition to one of the world's most unwelcoming realms. The quest to deploy seismographs extends far beyond the red dust of the Outback, taking us to the floor of the Southern Ocean, to a spot positioned precariously between Tasmania and Antarctica. The chapter unfolds with accounts of a two-week quarantine in Hobart, followed by our voyage to the Macquarie Ridge Complex that separates the Pacific from the Australian tectonic plate. The ridge itself is an imposing underwater barrier that stands as the steepest of its kind on Earth's surface. Here, the fierce Antarctic Circumpolar Current, driven from the west and carrying the waves more than 10 meters high, collides with the ridge. This turbulent sea, where sailors have only the mythical sea nymphs to rely on, becomes the stage for our dramatic expedition. My research team faces some of the most extreme ocean currents, waves, and winds on the planet. Seasickness decimates the crew. Amid these harrowing conditions, the operation to place seismographs on the ocean floor becomes a test of endurance and resolve. The search for the MRO21 ocean bottom seismometer, which, after becoming uncontrollably adrift, adds an extra layer of challenge to the mission. The chapter paints a stark picture of the obstacles faced in the pursuit of science, set against the backdrop of one of the Earth's most unforgiving environments.

In chapter 10, we complete our journey, returning full circle to the origins of our story about planets and their formation. Driven by humanity's relentless desire to conquer new worlds, we set our sights on the Moon, guided by the heroic figures of astronauts Armstrong, Aldrin, and Collins from the Apollo mission. Their footsteps on lunar soil mark a pivotal moment in our exploration of space. From the Moon, we turn our gaze to Mars, the red planet that has long captured our imagination. Beneath its crimson dust, we seek evidence of ancient life and ponder the mysteries of its vanished magnetic field. Why did its magnetic field cease to exist? Is Mars's interior still geologically active?

We employ the most advanced techniques and commit our resources to uncovering these secrets. The InSight mission, equipped with a modern seismograph, embarks on a journey to Mars that far surpasses the capabilities of the Viking missions. Armed with the latest advancements in global seismology and our refined understanding of Earth's interior, my research group makes two significant contributions along with those of the Insight team and other researchers: First, the inferred Martian events that repeat in the same locations suggest that Mars's interior is still mobile. Second, by employing the waves that reverberate hours after they are generated by marsquakes and, with the help of mathematical tools, we confirm the existence of Mars's core. I should add here that I stopped writing in early 2022, and only a few edits were made for the material published after that date.

As we look to the future, we envision a time when the methods and knowledge we have perfected on our planet will be applied in missions to the far reaches of our Solar System. Our blue planet, the third marble from the Sun, will continue to be the foundation for our exploration—our home lab, as we carry the legacy of scientific discovery to new and distant worlds. I hope that *When Worlds Quake* will give you a glimpse of what that discovery might look like and, perhaps, inspire you to be a part of it.

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