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Chapter Two:
The More Things Remain the Same, the More Things Change:
The Continents and Continuity, Isostasy and Otto Tittmann

After his three eventful years as Superintendent of the Survey, Henry S. Pritchett accepted an offer to become President of MIT and departed Washington. He was replaced by Otto Hilgard Tittmann (1850-1938), who served as Superintendent from 1900 to 1915. Tittmann's career embraced the old and the new. In a sense he was born in the Survey (he was actually born in Ohio) as he was the nephew of Julius Hilgard, the Survey's fifth Superintendent (1881-1885). He joined a Survey field party at the age of 17, in the year that Bache died, 1867. By 1900, when he became its leader, working for the Survey was the only job he had ever had. By the time he retired, he had worked for the Survey for 48 years.

Tittmann faced into the Survey, and he also faced out. His career emphasized the increasingly international nature of the Survey's burgeoning scientific work, as well as the opportunities that opened up for a person of his abilities and skills. He served on many international commissions, including the International Boundary Commission and commissions related to scientific standards, including the standards for substances assaayed by refractometer, including a refractometer originally invented by his uncle Julius Hilgard[1]. He was in charge of the Office of Weights and Measures in the Survey from 1887 to 1895, and in 1890 he was commissioned to bring the National Prototype Standards from Paris to Washington. Under his leadership in 1901, the Office of Weights and Measures separated from the Survey to become the National Bureau of Standards (NBS), as Pritchett had planned during his tenure. The physical meter has long been replaced by an optical standard length, but the one and only official kilogram of the United States, brought by Tittmann, still resides at the headquarters of the National Institute of Standards and Technology (NIST), the successor to NBS, in Gaithersburg, Maryland. Tittmann co-founded the National Geographic Society, and when he retired as Survey Superintendent in 1915 he became President of the Society until 1919. He also was a founding member of the Cosmos Club, an influential club of men of accomplishment in Washington, and served as the Club President in 1904. He was a member, and often a leader, of every major scientific society relevant to his subject areas,

[1] Garner, 1938, p. 394.

and served on the special committee of the NGS that evaluated Admiral Peary's claim to have reached the North Pole in 1909. Tittmann calculated that Peary had done so[2].

Tittmann's career and life were relentlessly straightforward that the only apparent drama in his life was a single episode, when he was a member of a field party of the International Boundary Commission. Tittmann and his crew were camped on a narrow defile above the Stikine River in Alaska. After a storm the water rose suddenly, and the men were able to scramble upwards to safety, but the entire camp and all their equipment and food were washed away[3]. In fact, Tittmann's career embraced many dramatic changes, but most of these occurred deep beneath the earth's surface. It was during the quietly productive tenure of Tittmann that the Survey acquired scientific missions, developed techniques and accumulated data that would, several decades later, lead to the most important upheavals in our understanding of the structure and functioning of the solid (or not so solid) earth itself. Tittmann's scientific life was coterminous with the rise and further rise of the calming concept of isostasy—but that same concept would eventually drive on relentlessly, like oceanic crust subducting, to create the great rift in the earth sciences that summoned the theory of plate tectonics itself.

The Survey in the US Government and the World

Apart from two short episodes when the Coast Survey was under the control of the US Navy, the Survey had been an agency in the US Treasury Department since Hassler's days. In 1903, the Coast and Geodetic Survey was transferred from the Department of the Treasury into the newly formed Department of Commerce and Labor, along with the National Bureau of Standards. In 1913, this Department was split into the separate departments of Commerce and of Labor, with the Survey and NBS remaining in Commerce. The Survey remained there the rest of its independent existence. In 1965 the Survey joined the Weather Bureau in forming ESSA (the Environmental Science Services Administration) in 1965, which became NOAA in 1970.

As the Survey had been the original scientific agency in the government, it was in many respects the template for other agencies as they developed. And all of these agencies were in turn affected by various attempts to standardize or regulate government bureaus as a part of specific administrations, particularly under periods of war. Perhaps the greatest cross-agency change in Tittmann's tenure was initiated by President Taft's 1910 President's Commission on Economy and Efficiency, which directed all non-military federal agencies to analyze their structures, and then strip away excessive infrastructure and expense. The Committee had a major impact, within the Survey, on the ways it administered its history and legacy. The Survey had generated vast quantities of data and information and charts, and also developed a major reference collection as well, particularly strong in several areas: historic maps and charts critical to resolve issues about boundaries and borders, and a premier scientific reference library, which formed around the core of the book collection that Ferdinand Hassler himself had assembled to conduct the Survey of the Coast. However, as a result of the 1910

[2] See Colton (1949) Garner (1938) and Tittmann (1916).
[3] Colton, p. 3.

Committee and its initiative, the Coast and Geodetic Survey removed thousands of its historic maps ands charts and other resources, and transferred them to the Library of Congress by 1914. This action probably "saved" and certainly better preserved much of the material, but it also dissociated the Survey from primary custodianship of its historical legacy, and it meant the loss of the "institutional memory" inherent in the existence of the major personnel with responsibilities for the Library and Archives Collection—when they left the Survey, their mastery of, or even knowledge of the existence of, the historical assets left with them.[4] This is an unfortunate theme that will arise again at various critical junctions in the history of the Survey and later of NOAA.

This attrition of maps and charts was accompanied by a parallel attrition in skilled members of the Survey, a seemingly constant problem since at least the demise of A.D. Bache in 1867. The Survey was the oldest scientific agency in the government, and as such was an important training academy for generations of scientists and skilled technicians, for computers and cartographers, for competent field party members and methodical librarians and catalogers. However—all of these personnel were necessary for other American scientific agencies and museums as they developed, and the Survey's ability to retain many or even sometimes the best of their personnel was severely constrained by the low salaries and limited rates of advancement that seemed to be endemic with work on the Survey. The history of the Survey is characterized by only a very few Superintendents or Directors who were capable of making substantial changes in these matters during their tenure, and Tittmann was not one of them. And thus it was as well that the opportunity of celebrating or even noting the centennial of the beginning of the Survey, in 1907, was passed by on Tittmann's watch.

In part this reflects the extraordinary advance in responsibilities for charting ever newer regions of the rapidly expanding American dominion. In part the Survey removed older maps from the Library and Archives Collection in order to make room for newer ones. The charting and geodetic responsibilities of the Survey continued to expand with the new territorial claims of the government. During Pritchett's tenure, the US acquired the Philippines and annexed Hawai'i, and the Survey acquired major responsibilities in both places, particularly so in the Philippines. The Survey became responsible for mapping the Panama Canal Zone in 1903. The impact of the Klondike gold rush on American and Canadian management of the Yukon River and environs led to major bi-lateral (meaning the US and Great Britain) largely cooperative enterprises to determine or re-determine various parts of the border between Canada and the United States. There were major International Boundary Commission surveying exercises in 1901, 1902, 1906, and 1913. These will be discussed further under the section on the Division of Geodesy.

The very technologies of map production and printing were changing under the feet of the Survey, as it were. During the "golden decade" 1851-61, the Coast Survey was one of the most important innovators in engraving and lithographic technologies in the United States. By the end of the century, the Survey had lost the lead in printing innovation, although that would change again in the 20th century as the Survey prepared

[4] Committee on Economy and Efficiency in Government (1911), R.M. Brown (1911)

for and fought the Second World War through charts and maps. In Tittmann's time, major printing innovations were developed outside the Survey, but eventually migrated into Survey practices.

The use of engraved copper plates as the primary "permanent" bases for Survey charts, which began in the 1840s, ceased in 1905, replaced by a variety of photographic media used to maintain the information content of the plates. Electrotype copies from older copper plates continued, so that charts continued to be printed from "copper" (which really meant electrotype plates). Also in 1905, photolithograph plates and presses were introduced. These could be used to print lithographs in multiple color runs, using dry paper, as opposed to the wet paper used with "copper", greatly expanding the speed of chart production while decreasing the distortions from wettened paper shrinking and expanding. Finally, in 1903, offset lithography applied to printing on paper was independently invented twice in the US, in one instance by the Harris Brothers. Eventually, the Survey and the Harris Press Co. would form a relationship that survives into the 21st century, but that event required the brilliant bureaucratic skills of Tittmann's successor.

These are the highlights of the Survey during Tittmann's tenure, ordered according to the "modern" divisions of the Survey that Pritchett had established during his tenure:

The Division of Hydrography and Topography

- in 1903, under the direction of Nicolas Heck, the technique of wire drag for detecting rocks and snags and other intrusions in the water was developed substantially, a technique that in largely similar form would be used by the Survey, and later NOAA, for almost the rest of the 20th century.

- The first experiments with underwater acoustics for detection and distancing began, in collaboration with the Submarine Signal Corporation.

- The national vertical and horizontal networks expanded, the former particularly rapidly using the newly invented Fischer vertical precise level, one of the finest Survey instruments ever created.

- A new tide prediction machine, developed by Richard Harris and perfected and implemented by Ernst Fischer, through a development process that lasted 15 years, was finished in 1912. The Tide Prediction Machine No. 2 (No. 1 had been the Ferrel machine) was one of the most sophisticated analog calculators ever constructed, and was used by the Survey until the 1960s.

The Division of Terrestrial Magnetism (and Seismology)

• The national system of magnetic observatories developed by Pritchett was realized under Louis A. Bauer, the first head of the Division of Terrestrial magnetism, with observatories in Sitka, Alaska, and Ewa, on the island of Oahu, in Hawai'i, standardized to the national observatory in Cheltenham, Maryland.

• Bauer wanted to extend terrestrial magnetic observations worldwide, and persuaded the Carnegie Institution of Washington to establish, in 1904, a Department of International Research in Terrestrial Magnetism, later shortened to the Department of Terrestrial Magnetism, or DTM. DTM and the Survey collaborated from then on.

• With Bauer moved to DTM, Nicolas Heck shifted from Hydrography to become the head of the Division of Terrestrial Magnetism, which led to decades of important work in the earth sciences, although Heck continued an important role in developing hydrographic equipment and techniques, especially Radio Acoustic Ranging (RAR) in the 1920s, along with major instruments for seismology.

• In 1906, the great earthquake of San Francisco occurred. Survey magnetic observatories used seismometers as part of their instrument arrays to determine what component of apparent changes in magnetic intensity (i.e., the variation of the needle) was attributable to earth movements. The data their seismological equipment yielded about the earthquake on the San Andreas Fault was impressive, albeit secondary to their primary task. Nevertheless, this brought the Survey into a prominent role in seismology, in cooperation with the Carnegie institution of Washington, especially in California, where resurveys of geodetic monuments yielded important data on earth movements along faults.

Division of Geodesy

• Survey latitude observatories located in close proximity to the 39th parallel of latitude near Gaithersburg, Maryland and Ukiah, California were formally incorporated in the International Latitude Service. This was a significant milestone in the increasingly internationalized, outward-looking science of the Survey.

• Based on the integration of the major great geodetic arcs run in the late 19th century, the Survey established the first national datum, the U.S. Standard datum, in 1901. The Survey persuaded the nations of Mexico and Canada to cooperate on a unified datum for all three countries, particularly driven by the efforts to extend the 98th Meridian arc from Arctic Canada on the north to the southwest coast of Mexico on the south, and by the US-Canadian effort, to determine the 141st meridian as the boundary between part of Alaska and Canada. These collaborations led to the declaration, in 1913, of the North American Datum, the first great international datum.

• As a part of this continental geodetic integration, John Hayford of the Survey began to develop a new model of the Figure of the Earth, the Hayford Spheroid, which was subsequently adopted internationally in 1924 as the International Reference Ellipsoid.

- Hayford and William Bowie developed a topographic method to adjust gravitational anomalies, associated with calculated deflections of the vertical, particularly related to re-calibration of stations of the great arc of the 39th parallel run between 1871 and the 1890s. The Bowie method became a world standard technique. Further, the gravitational anomalies were yet further reduced by applying various corrections based on the theory of isostatic equilibrium. The great success for the corrections amounted to substantive evidence for the theory of isostasy, which had huge implications for the controversies to arise and subside in the next critical decades of debate in all fields of geophysics.

- A great explosion in geodetic instruments occurred, not the least of which was the first use by Survey personnel of one of the most important geodetic instruments of the 20th century—the automobile.

Hydrography by Wire and Predicting Tides with Wire: The Division of Hydrography and Topography under Tittmann

The tools used for hydrographic and topographic surveying in this era were not radically different from previous technologies, but were improved over previous models. Much of this was due to the work of Ernst Fischer (1852-1934) and the personnel in the Survey's Instrument Division. Fischer was a child of German immigrants, born in Baltimore, who left with his family for Germany at 2, returning to the United States after a rigorous polytecnic school education and much work in engineering. In 1887 he joined the Survey, and very soon was chief of the Instrument Division, a position he held until his retirement in 1922. Fischer designed and improved many dozens of instruments used in every endeavor of the Survey on land and sea.

Two of these, from the Tittmann era, deserve mention. The first was the Fischer Precise Level, used in extending vertical control networks. It was cheaper, lighter, easier to use, and far more precise (hence its name) than any previous level model used in surveying and topography. Recognition of its significance requires some attention to vertical datums and how they differ profoundly from horizontal datums. The major work of the Survey, since the beginnings under Hassler, was to determine the specific positions of very specific important points, and then develop a triangulation grid radiating out from those points. The network was three-dimensional, in the sense that it followed the landscape, but the locations of the points in the network were the specifications of the horizontal positions of those points, relative to a specific reference ellipsoid and a specific datum. The vertical position of the points, as relative to mean sea level or its equivalent (the geoid) was a completely different matter, and a different kind of data, obtained by the use of completely different instruments. Vertical datams began at the seashore, with a zero level of mean sea level as defined by the average of years of tidal data to compensate for the influence of the Moon and sun and weather. Once mean sea level had been established, elevations above (and occasionally below) mean sea level marching inland were determined by spirit levels and calibrated rods. The vertical network could intersect the horizontal network, as when a spirit-level defined elevation was determined for a specific horizontal network point, but the determination of horizontal and vertical positioning for that single point were entirely distinct. Spirit-level positioning was clearly a function of the accuracy of the spirit-level, and the new Fischer instrument issued in a new era of advances in the vertical networks. Historically, these networks began at the coast, and advanced inland along routes chosen for the strategic and transportation significance of the route. In Tittmann's era, the most developed and densest vertical networks advanced along the Mississippi River and its tributaries, with smaller networks advancing uphill from Chesapeake Bay and its major tributaries, and adjacent to the major canals, like the Erie and Delaware canals, and along the important trunk railroad lines, especially the main line of the Pennsylvania River.[5] In each case, a specific spirit-line leveling survey marched inland and uphill from specific coastal points. A major research objective was to determine if sea level was the same for the Atlantic and Gulf coasts. There was much speculation that ocean circulation patterns and geography "piled up" water in the Gulf of Mexico, such that sea level there would be higher than sea level along the Atlantic coast. Four surveys run in 1893 and 1894 disclosed that the Gulf of Mexico sea level was a mean of 0.2585 meters higher than sea level on the Atlantic, but it wasn't clear that the accuracy of the leveling warranted a definite conclusion.[6] Adolph Lindenkohl, now working in his 4th decade with the Survey, attempted to determine differences in specific gravity (density) of surface sea water on the separate coasts in order to answer the question. His data was inconclusive for determining sea level, but hugely important for the subject of global ocean circulation and patterns of salinity and temperature.[7] These matters of determining mean sea level for specific seas and their relation to other seas, and the leveling networks running up from the ocean, would continue to be major research frontiers for the Survey and later for NOAA.

The second major instrument associated with Fischer was the great Tide Prediction Machine No. 2, the successor to Ferrell's Tide Prediction Machine No. 1. The second machine began with design work by R.A. Harris, and then Harris was joined by Fischer in the effort (later on, they disputed their relative contributions to the device). The Machine was, simply put, one of the most sophisticated analog calculators ever made. The input to the machine was historic tide data for at least a 19 year tidal cycle, which was then encompassed in a 39-term spherical harmonics expansion. The sun-moon-earth geometry for any arbitrary date for that place could then be entered, and the device cranked (literally) to produce the curve of the tides for that specific date and place. The Machine was used in both world wars, and continued in service until the middle 1960s, when digital computers finally made the machine obsolete[8].

A third technology developed for hydrographic surveying in this period represented a major advance for the Survey and the safety of navigation of any mariners using Survey charts. It also marked the debut of one of the most remarkable scientists in the Survey in the 20th century—Nicolas H. Heck (1882-1953). Heck was born in

[5] Hayford, 1898-99.
[6] Ibid., p. 397
[7] Lindenkohl, 1895.
[8] Schureman (1958).

Pennsylvania, graduated from Lehigh University, and then joined the Survey, where he remained for the next 40 years. Heck was a great enabler, a designer and improver of instruments and technologies. His contributions to the Survey spanned hydrography, terrestrial magnetism and seismology (he spent 20 years as head of that division) and the larger earth sciences, but they began with the perfection of wire-drag.

Hydrographic surveying when Heck began was changed little from the days of Hassler. Horizontal positioning of a Survey boat was determined by triangulation of visual observations of signals at known locations on land or in the water. Vertical lead line soundings at that position gave the depth. But between two different points, there was no data at all about the depth to the bottom, or the possibility of snags or protrusions or other dangers to mariners in between the surveyed points. In the 19th century French hydrographers had worked on techniques to sweep a mast or other straight object weighed down to a certain depth, in order to catch the mast on any potential obstruction. In the US, Army hydrographers in the Lakes Survey tried their own variant on this, called wire-sweep. When Nicolas Heck entered the Survey, he took on the task of adapting the technique to the constraints of the Survey, and making it work efficiently. The basic concept of a wire-drag is: a wire maintained at a determined depth by a combination of floats and weights is pulled or dragged through the wire between two work boats. Should any part of the wire encounter a significant obstruction or hit the bottom, then parts of the system float to the surface or otherwise indicated clearly and quickly that something has been encountered. A third boat (or more) then goes to the site of the obstruction to mark its position and depth. If the area is dragged without encountering an obstruction, then data has been obtained about the relative freedom of obstruction (at that depth) of the area, and this can be mapped as such. Heck developed the technique until it worked reliably, then he fine-tuned it in a series of successive improvements, addressed to the different constraints of three different classes of work—"first, to determine whether an apparently open sea is free from obstruction; second, to find the least water in a shoal area; third, to develop the maximum safe depth in a channel".[9] The idea was relatively straightforward, but its execution required a seemingly infinite series of tiny design improvements, for submerged floats that would surface when they encountered just the right tension on a line, etc. By patiently analyzing progress or the lack, and making a myriad of tiny improvements, Heck eventually developed the wire-drag technique to the point where the wire drag arrays could be as long as three miles wide as dragged through the water. Wire-drag was successful enough that the system, essentially the same as in 1904-07 when Heck developed it, was used by the Survey, and then by ESSA and then NOAA, until the final years of the 20th century.

Finally, during the latter years of Tittmann's tenure as head of the Survey, some applications of ocean acoustics began. Reginald Fessenden and the Submarine Signal Company were the pioneers in the uses of sound in the ocean for signalling, and then later for sound and sound echoes to indicate distance through the water. The Survey had long associations with the Lighthouse Service, and through its responsibilities for navigation and the avoidance of dangers, the Survey began to experiment, via equipment of the Submarine Signal Co., with acoustics. These efforts redoubled after the loss of the

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[9] Heck (1914, p.3)

Titanic in 1912. Fessenden designed an acoustic broadcast and receiving apparatus designed to echo horizontally off icebergs at the surface—but the system also noted echoes off the bottom, which could yield the ocean depth[10]. Only beginning experimentation with this revolutionary technique for hydrography occurred during Tittmann's tenure. However, with the literal explosion in ocean acoustic research by all sides in World War One, and the energy and drive of Tittmann's successor, the Survey was about to enter an entirely new world of acoustic surveying and mapping that continues to the present as the very foundation for most NOAA operations at sea.

Steaming from Manila: The Unique Case of the Philippines Coast and Geodetic Survey

As a result of the Spanish-American War, and also the great expansion of shipping in areas like the seas adjacent to the Yukon Territory and the newly opened Panama Canal Zone, the Survey acquired responsibilities for charting vast areas of new territories in both tropical and near polar waters. Of all the new areas to be charted, the case of the Philippines was in a class of its own.

The Coast and Geodetic Survey's new responsibilities for charting the Philippine Islands were enormous; the archipelago contained thousands of islands, and they were located on the other side of the Pacific Ocean from the United States. This effectively "opened up" the entire north Pacific Ocean to Survey ships and crews, going and coming from the west coast, Alaska, Hawai'i, and the other American island possessions, and the Philippines. As the relatively overworked and underpaid Survey staff members were commonly rotated through tours of duty in many disparate sites, they acquired experience in many different environments, which would become particularly critical decades later during World War II.

The legal and political context of the Philippines was complex. The Philippines had been a colony of Spain, now captured by the United States. A local revolutionary struggle for independence appealed to the United States to grant independence. The United States agree to do so—within 50 years. The revolutionaries then turned against the United States, mounting what the Americans termed an insurrection. This put the United States in the unusual situation of fighting to suppress a revolution in a colony that the US had pledged to grant their independence eventually. The first US Survey personnel arrived during the insurrection, and their immediate tasks were to assist military vessels fighting the insurrection. However, this meant that deep-draft boats were sent to unknown harbors hitherto used only by fishermen, which quickly led to a realization that the primary function of the Survey should be its traditional strengths in geodetic surveying and hydrographic charting. The Survey compiled the full archives of British and Spanish maps and charts, but it was recognized immediately that these were not accurate enough to suffice[11]. The Survey was brought in to develop a geodetic network and chart the insular waters and harbors, but it would do so working on behalf of

[10] Bates (1982)
[11] The Survey reprinted a revised Spanish language atlas in 1900 as C & GS Special Publication No. 3, unique in the history of the special publications. (US Coast and Geodetic Survey, 1900)

a new enterprise in the Philippine government, the Philippines Coast and Geodetic Survey, headquartered in Manila. As interior regions of many of the islands were inaccessible because of the rebellion—and also the challenges of Philippine geomorphology and tropical ecosystems—the Survey started by charting significant ports an harbors, then spreading out from them along island coasts. Eventually the major rebellion ended, and more "normal" working conditions and objectives could develop[12].

The challenges of the Philippines Survey were unique in American experience, as the country's islands ranged in size from almost the largest on earth to tiny atolls, occupied by large populations of people speaking many languages, although these populations were heavily concentrated on the west coasts along the China Sea, while the east side of the Philippines archipelago was much less settled, less developed, and much more remote. E.R. Frisby, a Survey senior hydrographer, wrote a memoir about the early history of the Survey in the Philippines. His descriptions of field work in the tropics are vivid:

"One raised in the temperate zone, educated in the high average social culture of America and not inured to the bodily hardships of tropical exploration, little conceives the first shock of contact with aboriginal life. Reconnaissance was often on all fours behind a gang of knifemen slashing a tunnel through matter underbrush; at other times, it was in stifling fields of giant grass so dense and tall as to exclude all views except that of the blasting overhead sun; and again, it was a problem of waist-deep slimy swamps. Physical effort in the warm and humid air bathed the body in perspiration; and contaminated water demanded that the torments of thirst be met with self-denial or with an unbearable load of canteens.

"Station clearing in dense hardwood forests turned the teeth of cutting tools and elicited amusement when severed trees refused to fall. Days of cutting were followed by days of disentangling the lacework of vines tangled in the tree tops.

"Camp life was a struggle against the personal discomforts caused by insects, skin infections and diseases, primitive lack of sanitation, and the prevalence of intestinal disorders and fevers. There was a pervading sense of helplessness in dealing with native inhabitants and in securing efficient work from native employees. Irritations were multiplied by the failures of language, the inertia of the people, and their inability to comprehend either the haste of the foreigner or the intricacies of the occidental methods. A sense of isolation and loneliness completed the undoing of all but the strongest spirits. It was natural that reports of these conditions, exaggerated by distance and repetition, should cause apprehension in the United States, with the result that numerous resignations occurred in the early days of the Survey as an alternative to three years of Philippine service.

"Fortunately, however, there are individuals of the pioneer type who delight in discomfort and revel in the curiosity and humor of strange and novel situations. Such men flocked to the original organization of the Philippine government—officers of the

[12] Putnam, 1907.

army and constabulary, engineers, teachers and provincial officials—and the similar elements in the Coast Survey enthusiastically carried its work through the early crucial and formative stages and pointed the way to its successful continuation."[13]

The Philippine Survey evolved a unique structure and work methodology appropriate to its novel context. The capable George Rockwell Putnam, who was later the Director of Lighthouses for the United States, was the founding director of the Philippine Survey, serving from 1901-06. All work was organized through and came back to the headquarters in Manila. Since the Philippines was so geographically distant from the United States, virtually all Survey data reduction and analysis, and chart construction and printing, was performed in Manila, not back in Washington, as was the case with the Coast Survey proper.

The tasks in surveying the new tropical areas were quite similar to those necessary for Alaska and the original surveys of the west coast. In the northeast Pacific areas, the human populations were sparse, and geodetic networks had to be begun from scratch. The Philippines had large populations of very diverse peoples, but geodetically the archipelago was as much a pioneer coast as California had been under George Davidson in the 19th century. Previous British and Spanish charting and positioning were inadequate to the demands of commerce and military needs, so once again the work started from scratch. The Coast Survey dispatched the hydrographic survey ship the Pathfinder, then the largest Coast Survey ship, from duties in Alaska to the Philippines. Although the *Pathfinder* had been especially designed for service in the cold waters off Alaska, it served for four decades in the tropical waters of the Philippines. After the ship was scuttled in Manila Bay in 1941, its original name was revived for a new survey ship, the legendary *Pathfinder* of World War Two[14].

The Philippine Survey paid a heavy price for its initial military-related work charting important harbors and island passageways without benefit of a central datum. The geodetic foundation for the Philippines Survey involved establishing "39 fundamental positions which served to fix all original separate surveys during the period they remained detached. These positions were well distributed over the west coast and central portions of the archipelago, but were sadly deficient along the east coast where lack of telegraphic facilities made longitude determinations impossible".[15] Thereafter, local topographic and hydrographic surveys were tied in to the 39 fundamental positions. This meant that, in effect, there were actually many local, disparate datums. Charts made using projections from the positions did not match. As Frisby noted, at one point there were 51 charts of parts of Luzon and its surrounding waters, based on 19 different positions. The work to develop a single Philippine datum converged on a geodetic network based on the island of Luzon (where Manila is situated) which could be expanded throughout the archipelago. By 1906 the Luzon Datum had crossed the waters to adjacent islands, where 19 astronomical stations were brought into geodetic connection. This early approximation, the Vigan Datum, was tightened and corrected over a period of many years, an arduous process. As Frisby noted, "details of the

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[13] Frisby, 1921, pp. 10-11.
[14] See Cloud (2006).
[15] Frisby, ibid, p. 7.

computations extending over several years are so voluminous and involved as to require separate presentation".[16]

Thus the Philippines Coast and Geodetic Survey developed, separate from the U.S. Coast and Geodetic Survey but also complexly inter-twined. The exchanges of personnel between assignments in Alaska, Hawai'i and the other island possessions, and the US west coast did result in a Survey that plied the northern Pacific Ocean continually, producing data that would eventually be fundamental to the conceptual upheavals of plate tectonics.

The Long Road from Cheltenham: The Division of Terrestrial Magnetism under Tittmann

There are three elements of terrestrial magnetism at any point on earth (the absolute magnetic intensity, and the horizontal (declination) and vertical (dip) components of the local magnetic field) and the only constant of the three is their continual variation, in response to changes in the earth's mass distribution and the planet's interaction with the magnetic fields of the Sun. Therefore, resolving the local magnetic field, at any given time, for any given point, requires the use of three sets of instruments designed to measure one of the three elements. These instruments must be calibrated to standards, but these standards are set using other instruments, which vary with the local fields. Hence Pritchett set operations in motion to develop a national network for magnetic observations and instruments, using the observatory at Cheltenham, Maryland as the national standard, with permanent observatories as well in Sitka, Alaska and Ewa, on Oahu, in Hawai'i, along with other observatories established for short periods in specific regions. It fell to Tittmann to realize the national observatory system, and to coordinate the growing and increasingly sophisticated practices of the Survey's Division of Terrestrial Magnetism with the new, internationally oriented Department of International Research in Terrestrial Magnetism of the Carnegie Institution of Washington, established in 1904. Louis A. Bauer was the head of the Division; he was also the founding director of the Department, a role he held until 1931.

There was an entirely cooperative relationship between the Division, in the Survey, and the Department, in the Carnegie Institution, because they were meant to play complementary roles. The instrumentation of terrestrial magnetism from the Survey side was constrained by the territorial responsibilities of the Survey, which had greatly expanded but were still confined to the land and seas of American possessions and territories. But Bauer wanted to acquire and assimilate magnetic data from around the globe, precisely outside those areas that would be the responsibility of the Survey. These goals were compatible. It also helped that, in 1906, shortly after the founding of the Department (hence DTM), former Survey Superintendent Pritchett was elected as a

[16] Ibid., p. 25.

Carnegie Trustee, and he soon secured a post on the three-member Finance Committee, much to the benefit of Bauer and his initiatives.[17]

The initial collaboration between DTM and the Survey involved development and standardization of instruments at Cheltenham and the other observatories. Later, in 1905, the DTM's first somewhat non-magnetic ship the *Galilee* (a converted brigantine from which much iron was removed and replaced with non-magnetic metals) was sailed under the command of the Survey's Captain J.T. Hayes from San Francisco to San Diego, then to Hawai'i and back to the mainland. On route the instruments were tested and procedures for their use formalized. At the end of this trip the Survey leaders decamped, and DTM personnel—which included former Survey personnel who shifted to DTM—continued alone for two other cruises. In 1908, the completely non-magnetic ship *Carnegie* was contracted, and completed and launched the following year. J. T. Ault became its sailing master and captain, a role he maintained to the very tragic end, dying in the fiery explosion of the vessel in 1929.

With Bauer's transfer from the Survey to DTM, Nicolas Heck, already mentioned for his role in developing and perfecting wire-drag, transferred to the Division of Terrestrial Magnetism, becoming its head for the next three decades. The magnetic observatories all contained seismometers as a part of the instrument array, so that local disturbances of the magnetic instruments attributable to earth tremors could be identified and compensated for. Providentially, then, the Survey's magnetic observatories, although not designed for seismological work as such, proved extremely important when the great San Francisco earthquake struck California in April, 1906.[18] The earthquake was named for the city of San Francisco because the damage there was enormous and apparent, but in fact a major slippage along hundreds of miles of the San Andreas Fault has occurred. In response, the Survey reoccupied primary, secondary, and tertiary points between Monterey in the south and Fort Ross on the north to create a new modified triangulation network, in order to determine the relative motion of stations due to the earthquake, the first application of the technique in the US[19].

The earthquake dramatically highlighted the necessity for major expansions in seismological networks and development of new techniques. The point was certainly not lost on Heck; eventually under his leadership the Division would be renamed the Division of Terrestrial Magnetism and Seismology, with primary responsibility for seismological research in the federal government. That expansion would require time, and the transition to the tenure of the next Superintendent of the Survey.

The Rise and further Rise of Isostasy: The Division of Geodesy under Tittmann

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[17] See Louis Brown, 2004, p. 3 This is the definitive history of DTM and quite useful for the story of Survey interactions with DTM until the end of WW II, at which time the Department of Terrestrial Magnetism abandoned the study of terrestrial magnetism, although it kept the name in its title.
[18] The earthquake was sensed and recorded on seismographs at C & GS magnetic observatories at Cheltenham, Maryland, Vieques, Puerto Rico, Ewa, Oahu, Hawai'i, and Sitka, Alaska. See Reid (1910).
[19] See Hayford and Baldwin (1907).

During the tenure of Tittmann, the Survey consolidated and expanded upon research activities developed through the 19th century to become recognized as one of the premier scientific agencies of the world. How its prominence eroded in subsequent decades and after subsequent wars is reserved for other chapters; here the emphasis is on this period as a geodetic flower unfolding.

In a sense the story is one of continual expansion in space and objective, as geodetic surveys turned into triangulation networks, then into transcontinental arcs, then national and then continental datums, then finally a model of the Figure of the Earth itself, culminating in the Hayford Spheroid. In another sense the story is one of the increasingly internationalized scope of the geodetic sciences, as instrument designs were standardized and promulgated to gather increasingly large and spatially diffuse data sets which were shared and collectively analyzed by national-level geodetic agencies and by international associations whose memberships came from the national bureaus .

This shift to increasingly international scope is exemplified in the history of the United States Datum. In the late 19th century, the original coastal geodetic networks were tied together by the great 39th parallel arc triangulation project, the last great enterprise of Charles Schott. Other arc surveys were developed, especially the Atlantic coast diagonal arc from Nova Scotia to the Texas-Mexico border, and the arc of the 98th meridian. As has been noted, arc surveys define not a line along a meridian or parallel of latitude, but rather a zone of triangles running along the line and determined in large part by the nature of the local topography. Very close to the intersections of the networks of the 39th parallel arc survey and the 98th meridian arc survey the Survey established a geodetic monument on a large private ranch in Kansas. That station, Meades Ranch (39° 13' 26.686" North, 98° 32' 30.506" West) was to become prominent in the entire history of geodesy and cartography in North America for most of the 20th century.

Under Tittmann, in 1901 the Survey proposed a national datum be established for the United States. A datum is a specific geodetic network schema associated with a specific reference ellipsoid model of the Figure of the Earth. “Datum” is the singular of “data”; Meades Ranch was the point where the American reference frame system would be pinned to the ground, as it were. Meades Ranch was chosen because it was very close to the geographic center of the lower 48 states, and because the local and regional terrain were as flat as could be found, minimizing the possibility of deflection of the vertical in plumb bobs at the site, which will be examined in much greater detail shortly. In effect, a plumb bob at Meades Ranch was defined, legally, as pointing directly to the center of the earth, as that center was defined by the Clarke Ellipsoid of 1866. That being defined, then the goodness of fit of the rest of the geodetic network radiating out from Kansas would be most accurate for the great mass of the American portion of the continent, with error pushed to the national margins.

At the same time, though, Tittman and the Survey sought to extend the network and its accuracy of positioning beyond the political boundaries of the lower 48 states by appealing to Canada and Mexico to join the United States in one unified continental datum. This effort was particularly driven by the efforts to extend the 98th Meridian arc from Arctic Canada on the north to the southwest coast of Mexico on the south, and by the US-Canadian effort, to determine the 141st meridian as the boundary between part of Alaska and Canada. These collaborations led to the declaration by all three countries, in 1913, of the North American Datum, the first great international datum. The survey work to complete the arcs, and the necessary reduction and calculations of the data took more than another decade, so that eventually when the initial resolution was finished, the result was the North American Datum of 1927, which was the continental datum for over half a century, finally replaced, in the era of satellites, by the North American datum of 1983 and the World Geodetic System of 1984, both of which were based on a point of origin at the center of mass of the earth, and oriented along the polar axis.

Thus the work of the Division of Geodesy under Tittmann reached standards as high or higher than anywhere else in the world, and attracted scientists of the highest calibre, particularly John Hayford and William Bowie. But this geodetic progress also suffused the Survey's activities in other divisions as well. As Bowie later noted: "any survey of the land in which the shape and size of the earth are taken into consideration can be called geodetic; thus the hydrographic surveys along the coast made for a sailing chart are really geodetic surveys and, similarly, a topographic survey of a large area may be considered to be a geodetic survey".[20]

Thus, as the Division of Geodesy expanded its scope of activities and its ambitions, these suffused the activities of the rest of the Survey. But the Survey and its leaders also impacted scientists and disciplines far beyond the traditional fields of geophysics, as Survey scientists, especially Division chief John Hayford and his associate William Bowie, theorized about and then tested, through re-analysis of classic Survey geodetic data, a set of concepts that arose in the second half of the 19th century, with far-reaching implications for practitioners in the 20th century. Their research brought the Survey to the very center of the struggle to propose, test, and evaluate the theory of *isostasy*, which proposed to account for the equilibrium of the continents and oceans in vertical movement. The concept of isostatic equilibrium became a driving force in geophysics for many critical decades, not withstanding the fact that the concept did little to resolve the larger battles about supposed horizontal movements of continents. These combined struggles to detect and understand horizontal and vertical movements together later on, in the middle 20th century, gave rise to plate tectonics. Looking back a long century from that, the significance of isostasy seems diminished. But, to its credit, the theory of isostasy was never succeeded by a rival theory, but instead by a body of data that largely corroborated the theory.

Isostasy will be described more fully later; what is important for the moment is why it was necessary and important. The word "isostasy" was coined by the geologist C.E. Dutton in 1889. Its meaning, derived from Greek, is "equal pressure" or "equal standing", and it refers to an evolving concept that the materials visible at the surface of the earth are supported by thicker, more fluid materials below them in some sort of globally regular manner. Isostasy arose as a conceptual solution to very tangible problems with the observation systems and results from high-order geodetic surveys.

[20] Bowie "A Survey of Research Problems in Geophysics" 1920, p. 546.

Assuming isostasy and modelling for it in specific ways allowed corrections to observations to be made that decreased errors and tightened the fit of geodetic networks to the real world, which is why the concept/theory arose and was applied. But isostasy, once committed to, had implications that suffused one's entire conceptions of the earth and how it worked. These matters worked out over many decades and involved the entire community of the earth sciences. But since isostatic corrections arose to address very specific problems in geodetic survey data, it is best to begin with a description of the array of geodetic survey techniques and instruments as they were pursued in this critical era of the Tittmann years.

Survey networks began as triangulation networks running along the different American coasts, wherever these were located as the nation and its empire expanded. Then larger and longer networks, called arcs (because they constituted arcs on the earth's ellipsoidal crust) tied together the networks. Starting after the Civil War in the early 1870s, the Survey's great arc of the 39th parallel was built across the continent to tie the Atlantic and Pacific networks together. The arc was a network of geodetic triangles, which is to say that its points were determined and positioned by measuring vertical and horizontal angles that took the Figure of the earth into account. At the same time, at various (but not all) of the network points, measurements of local relative gravity were obtained using an instrument developed by former Superintendent Mendenhall of the Coast and Geodetic Survey, a set of reversing pendulums carried in a near air-tight case to minimize the effects of atmospheric drag on the pendulums. At the same time, a small number of critical observation stations distributed across the length of the arc survey were designated Laplace stations, in honor of the great Marquis de La Place, the French polymath who, in his masterpiece *Mecanique Celeste* had extended and corrected the schema of physics of Isaac Newton and the other pioneers of celestial mechanics[21]. A Laplace station is a site where rigorous astronomical observations are made over enough time and with sufficient reduction of the data, to determine the astronomically determined position of the observation station. This is then compared to the geodetically determined position of the station, based on the positions of a myriad of points in the network.

There are three bodies of potential error, which is to say disagreement, between the astronomic and geodetic positions. Specific errors in the geodetic network of points on the ground may result in a geodetic position differing from the "real" position determined astronomically. However, the astronomically-determined position is based on the notion that a plumb-bob at that point points to the very center of the earth. This can be in wrong, for (at least) two reasons, each of them distinct. First, on any volume except a perfectly formed sphere, a plumb bob perpendicular to the local level may not point to the geometrical center of the Figure of the earth because of the shape or elongation of the planet—to the extent that the earth is not spherical, there will be disparity between the direction the plumb bob points and the earth's center of mass.

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[21] La Place published Mecanique Celeste (Celestial Mechanics) in 5 volumes, 1799-1825. The book was notorious for its sketchy presentation of equations and their derivation (LaPlace, 1799-1825). Over decades Nathaniel Bowditch, the author of the American Practical Navigator, prepared a translation and commentary on the work. His version, published over the years 1825-1839, is one of the classic works of American science (Bowditch, 1825-39).

Second, the plumb bob may be perpendicular to local gravity, but local gravity is affected by differential balances of local masses, like mountain ranges and sea shores, which cause the plumb bob to point away from the reference vertical. Both of these influences will result in a disparity between the positions of the same spot, as calculated astronomically and geodetically.

A Laplace station is one set up to determine and then compare astronomic and geodetic positions and then deal very systematically with the differences in positioning revealed by them. These Laplace stations are scattered strategically around the full network, so that the errors determined through rigorous analysis of a few such stations may in turn be applied to most or all other stations in the network. The deflections of the vertical at a number of Laplace stations can be used for astro-geodetic orientation. A Laplace station is defined as a triangulation or traverse station at which a geodetic (Laplace) azimuth is derived from an astronomic azimuth by use of the Laplace equation. The Laplace equation expresses the relationship between astronomic azimuth, geodetic azimuth and the astronomic longitude and geodetic longitude. Although it is not in the definition, the astronomic latitude is normally observed at each Laplace station. In an orientation of this type, a correction is made at the origin (initial point) which in effect reduces the sum of the squares of the astro-geodetic deflections at all the Laplace stations to a minimum[22].

Hence, as the 39th parallel arc survey proceeded, at certain critical points, astro-geodetic positionings were obtained, along with values for relative gravitational attraction at these points. Certain classes of corrections of the positionings were computed during or immediately after the arc survey. However, the entire matter was revisited, first by Hayford, and then by Hayford and Bowie, in order to correct for errors in the positionings at the Laplace points and across the network, based on characterizations of both the top and the bottom of the land surface segment on which the points stood. Corrections at the top involved local gravity and the slope of the local geoid (an equipotential surface of gravitational attraction, of which the classic and most common is sea level; hence, the geoid under elevated continental lands would be the conceptual surface of sea level should the sea be extended into the continent via great ditches or the like)[23]. Corrections at the bottom of the column of planetary crust segment involved the complex concept of isostasy.

Isostasy was and is a brace of theories that were designed to explain the mechanisms by which continents stand higher than ocean basins, and to what extent these phenomena are in equilibrium. Their further extensions led to the great debates of the 20th century about the possible movements of continents which in turn led to speculation and debate about the very nature of the earth's crust and its organization and dynamics. Interestingly, though, all this began with the effort to resolve and explain errors in another geodetic survey in the middle of the 19th century.

[22] See the modern classic *Geodesy for the Layman* for further explanation of these basic geodetic terms.
[23] Geodesy for the Layman, ibid.

The Great Trigonometric Survey of India included a geodetic network arc that marched from the Indian Ocean north to Mount Everest, named for the Survey's original director. Survey geodesists assumed that the great mass of the Himalayas would deflect the plumb bob towards the mountains, so they estimated the masses and degree of deflection they expected. The deflection was significantly less than their estimate. Counter-intuitively, at the arc's southern end, by the Indian Ocean the plumb bob was found to be deflected towards the ocean, which had not been expected. What explanation could account for the disparate deflections at either end? Two of the greatest earth scientists of the century, J.H. Pratt, then the Archdeacon of Calcutta, and the British astronomer G.B. Airy, developed opposing yet related theories that the deflections of the vertical were caused by different densities of planetary materials around the point where the plumb bob was hung, and that these blocks of earthly crust of different density essentially floated in equilibrium on a deeper fluid layer. The Pratt and Airy models differed on how and where equilibrium occurred, with the Pratt model proposing blocks of varying density floating at a uniform height, while the Airy model proposed blocks of uniform density floating at varying depths. The main point is that they opened the topic of the structure of the earth's crust and the concept of equilibrium, and the processes of vertical movement in the crust, a debate that has continued to the present era[24].

Now we can deal more specifically with the Airy and Pratt models for the compensation of continents and islands. In Airy's conception, land masses rest hydrostatically on highly plastic materials below, with roots projecting into the lower material; hence the greater the projection above the surface, the greater the unseen root below supporting it. In Pratt's conception, the land masses project above the average elevation because they are on material of less density beneath them, and so the higher the surface materials project, the less dense are they and the roots beneath them. These disparately dense materials are supported, ultimately, by material at depth in a transitional state from solid to fluid. In the Pratt model, the masses of material of varying density are supported at a uniform level at great depth, called the level of compensation. Therefore, less dense materials would extend higher above the uniform level of compensation, while denser materials would extend to a lower point. Common to both Airy and Pratt is the notion of equilibrium—one way or the other, masses of materials of different density are supported above a plastic media at great depth, and apart from relatively transient disturbances these materials remain in equilibrium, relative to vertical motion (as opposed to horizontal motion, which became the source of bitter debate in subsequent decades).[25]

Geodetic surveys in India had yielded data about local gravity indirectly, through the plumb bob's deflection of the vertical. In the 1870s, pendulum instruments to measure local gravity (but not necessarily its orientation) were developed. The Coast Survey's polymath Charles Sanders Peirce developed the initial gravity program within the Coast Survey, in the classic style going all the way back to Ferdinand Hassler. Peirce traveled to Europe to secure instruments and materials, then calibrated his pendulum apparatus against the gravity standard at Potsdam, near Berlin, which was the world

[24] The primary documents in this are Airy (1855) and Pratt (1855, 1859).
[25] See Bowie (1927) for a useful presentation of the history of the concepts of isostasy.

standard. Upon his return, he organized gravity measurements as important constituents of Survey geodetic work. In less than a half-decade, his analysis of gravity data yielded deductions about the Figure of the Earth.[26] Around 1885, Von Sterneck invented an apparatus consisting of a short pendulum swung in a case in a partial vacuum, and the absence of friction through air resistance allowed the apparatus to be used to detect difference sin gravity between two stations with a high degree of precision. Around 1890, Thomas C. Mendenhall, while working as the Superintendent of the Survey, developed an improved version of the compensated pendulums apparatus that remained the major gravity instrument for at least the next 30 years.[27]

Precise geodetic surveys overland in India had first revealed disparities in gravity that pointed to disparities in density of the materials at the earth's surface that were correlated in some way with conditions at great depth, although direct evidence from the depths was impossible to obtain. The next major phase in geodetic discovery on these matters involved surveys on coasts and islands, which is to say, the nexus of continental masses and oceanic crust. The Coast and Geodetic Survey here came into its own as a player, which is to say as a generator of data and purveyor of theory. Much of the work in surveying was organized by George Rockwell Putnam, who later was director of the US Lighthouse Board, and Erasmus Darwin Preston, who pioneered gravity surveys on islands in the Pacific Ocean, and then later the Atlantic Ocean. These Pacific islands included new territorial possessions of the United States, and also the Kingdom of Hawai'i, where the Survey initiated cooperative projects with the Government Survey of Hawai'i almost a decade before the annexation of the Kingdom to the United States.[28]

The isostatic debate may be seen as an element of an increasingly internationalized and cooperative process linking national institutions and individuals into global scientific organizations. In 1886, the geodetic association originally founded by the German state of Prussia, which eventually expanded to include other European states, thoroughly internationalized as the International Geodetic Association. From that point on, the annual conferences of the IGA became major venues for presentation of new data and analysis by Survey scientists, as well as sites for discussion of the latest theories and newest controversies in geophysics. In was in this context that Dutton, in 1889, coined the term "isostasy" to refer to this great nexus of data and contention.

With the Spanish-American War, the US acquired Puerto Rico, and soon the Coast and Geodetic Survey acquired responsibilities for surveying the island and its context. The astronomical latitudes of San Juan, on the north, and Ponce, on the south, were determined. The north-south component of the distance between them was about 30 miles. The distance between them computed by their astronomic positions was almost a mile compared to the distance computed by triangulation between them. The disparity was caused by the deflection of the vertical in plumb bobs positioned at the two sites, on either side of the great mountainous land mass of the island, next to depths of the Atlantic

[26] See Peirce (1876) and (1881).
[27] See Mendenhall (1891) and Bowie (1920).
[28] See Putnam (1894) and Preston (1883-1893).

and Caribbean, respectively, on the north and south[29]. Apart of the disparity was the lesser density of sea water than island rock, and there were indications that the submerged rock masses beneath the seas were denser than island rocks. Clearly the matter of the differences in density of the masses at the surface of the earth, and their complex relationship to the yielding materials at depth, would have to be analyzed to the point of a solution if the Survey was to progress.

Around 1904, then, Tittmann authorized Hayford, in his capacity of Chief of the Computing Division of the Survey, to begin a project to re-visit the data from the 39th parallel arc and other Survey networks, as an "investigation of the figure of the earth and of the reality of the condition called isostasy... based entirely upon observed deflections of the vertical in the United States".[30] The geodetic reference system was the new United States Datum with origin at Meades Ranch, Kansas, using the 1866 Clarke Ellipsoid. By comparing the astronomic and geodetic positionings of major point in the arc, and assembling the astrogeodetic disparities in position, the deflection of the vertical could be characterized for each major point.

The process involved three major stages. First, the astronomically derived position of any given point was based on the alignment of stars at certain times, but that alignment was based on the vertical as defined by the orientation of a plumb bob at that point. If the geodetic position of that same point, based on the triangulation network, was significantly different, it was evidence that the plumb bob at that point was not pointing to the earth's center. That difference in orientation was the deflection of the vertical at that point. Second, Hayford devised a system of partitioning the land mass around the point in question, with radiating sectors and concentric rings. The local topography was partitioned into the "boxes' defined by the segments—a mountain in a segment would be an excess of mass, a valley would be a deficiency of mass, etc. The sum of these segments, calculated out to a radial distance big enough to capture most of the topographical deflection bearing on that point (the interpolation distance out varied depending on local and regional topography) would give, at the end, an estimate of the local topographic deflection of the vertical, which could then be compared to the astrogeodetic deflection of the vertical. Third, and most important, given the fact that the astrogeodetic deflections tended to be systematically smaller than they should have been, based on the topographical deflections calculated, the principal of isostasy was invoked. "Isostasy must be considered. The logical conclusion from the study from the study of the geoid contours for the United States, taken in connection with the fact already noted that the computed topographic deflections are much larger than the observed deflections of the vertical, is that some influence must be in operation which produces an incomplete counterbalancing of the deflections produced by the topography, leaving much smaller deflections in the same direction. There is abundant evidence in the literature of geodesy indicating that this relation of observed deflections of the vertical to the topography is not peculiar to the Unites States; that, in fact, it exists everywhere". [31]

[29] Bowie, 1920, p. 547.
[30] Hayford, 1909, p. 10
[31] Hayford, 1909, p. 65.

Evidence may have existed everywhere, but the perception of that evidence and insistence on its significance was and is another matter. Thus, we must recognize the entrance of William Bowie to the stage of the full exertion of his considerable powers. John Hayford had been made chief of the division of computing in 1898 by Superintendent Pritchett. He served as chief under Tittmann until 1909, when he left the Survey to become head of the College of Engineering at Northwestern University. He was replaced as chief of the computing division and inspector of geodetic work by William Bowie, who had entered the Survey in 1895, after university studies at Trinity College. Bowie became a giant in American science in the 20th century, and he rose to these heights with isostasy.

Hayford left the Survey for a more secure and academically recognized position, and possibly also because it was clear that Bowie's time to rise had come. They continued to work closely in any case, and in 1912 they jointly published the treatise that secured their reputations and marked the triumph of isostasy.[32] The work was an extension of Hayford's topographic deflection work, only applied to the other end of the topography, as it were. It will be recalled that the concept or theory of isostasy was devised to address the fact that different portions of the earth stood high or low, and the relative stability of their positions in geological time indicated a good degree of equilibrium in their states. That equilibrium implied an overall balance in the system, i.e., that lighter, less dense materials floated higher on top of deeper materials and lower, more dense materials floated lower. Since the differences in densities of portions of crust at or near the surface could not account for the deflections of the vertical actually observed, that implied that the disparities in density continued down deep below the surface. The Pratt model of isostasy proposed that all these crustal blocks, of varying density, floated at about the same depth everywhere, the uniform level of compensation. Bowie and Hayford's next major step was to estimate the depth of the uniform level of compensation for the North American data, and to so by bringing to bear data on the intensity of gravity, as measured at certain stations along the Survey arcs, using the Mendenhall pendulums. As they stated: "logically the next step to be taken was therefore to introduce such a definite recognition of isostasy into gravity computations. Moreover, it appeared that if this step was taken it would furnish a proof of the existence of isostasy independent of the proof furnished by observed deflections of the vertical, and would therefore be of great value in supplementing the deflection investigations and in testing the conclusions drawn form them. In other words, the effects of isostasy upon the direction of gravity at various stations on the earth's surface having been studied, it then appeared to be almost equally important to investigate the effects of isostasy upon the intensity of gravity".[33]

The Hayford-Bowie project involved correlating a geometrical reference system for the earth, which became the Hayford Spheroid, which in turn became the International Reference Ellipsoid, the internationally recognized reference ellipsoid until the postwar era of satellites, with the actual North American triangulation networks of the Survey and their thousands of points, the several hundred points for which both

[32] Hayford and Bowie, 1912.
[33] Ibid, p. 5.

astrogeodetic and topographical deflections of the vertical, and finally the 88 stations for which gravity intensity was obtained[34]. Various systems to estimate density of crustal blocks were used, along with various types of corrections to gravity intensity anomalies (free-air, Bouguer, etc.). Finally, different estimates for the effects of levels of compensation at different depths were applied (imagining these different levels of compensation to be onion layers at different depths under North America). They had to make major assumptions about average density of crustal materials as depths for which there was not, nor ever could be, any direct measurement. But, at the end of the day, they found that, assuming certain densities, and assuming a level of compensation around 113 kilometers below the surface, they could account for most of the differences in both the deflections of the vertical and the gravitational anomalies measured at the major stations.

It is with difficulty that we, now, can appreciate the nature of their achievement and also its profound impact on the earth sciences of the era. Essentially, the theory of isostasy arose in response to the complete absence of sufficient data about the earth at depth necessary to explain the patterns of data obtained at the surface. Isostasy involved the assumption about various aspects about how the earth system worked. Hayford and Bowie proposed that, making that assumption, and calculating values based on the assumption, the theory of isostasy could explain the coherent and systematic patterning of otherwise anomalous data from two independent (but related) phenomena—deflection of the vertical, and gravity anomalies. Given this, they could then approximate the portion of the geoid running under the continent of North America, and they could project from that continental portion an estimation of the figure of the earth. As it happened, the shape of North America is anomalous, and this introduced substantial error into their estimation of both the size and the shape of the figure of the earth. The error in size was soon recognized through the results ofvery long arc surveys on other continents, but it would take half a century and the advent of satellites to disclose the error in the shape of the earth. And as it happened, the apparent triumph of isostasy was a major element of larger and exceedingly complex battles about horizontal movement and equilibrium, in addition to vertical movement and equilibrium, which would be played out in terms of continental drift and then plate tectonics. In that context, the arguments of many players, most especially Bowie, would be swept away in later decades. Nevertheless, in that moment, in the final years of the long tenure of Otto Tittman as Superintendent of the Coast and Geodetic Survey, it was as though the Survey had occupied a very high peak, and that point on that peak was a very important point, brought into a very important network, in a world in isostatic equilibrium, at the very least.

But that world was in no other form of equilibrium, and would soon be swept into world war, world depression, and major changes in the roles and significance of the Coast and Geodetic Survey. The Survey would change and expand and tackle whole new projects and responsibilities, under the direction of a very different man. Otto Tittmann was a magnificent exemplar of the Survey, but his era was quickly succeeded by that of his successor, the most important director of the Survey in the 20th century, the one

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[34] There were actually 89 stations, but two of them, at Seattle, were so close to each other the data from one station only was used. See footnote, Ibid, p. 113.

person in the history of the Survey most directly comparable to Alexander Dallas Bache. The era of E. Lester Jones was about to begin.

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