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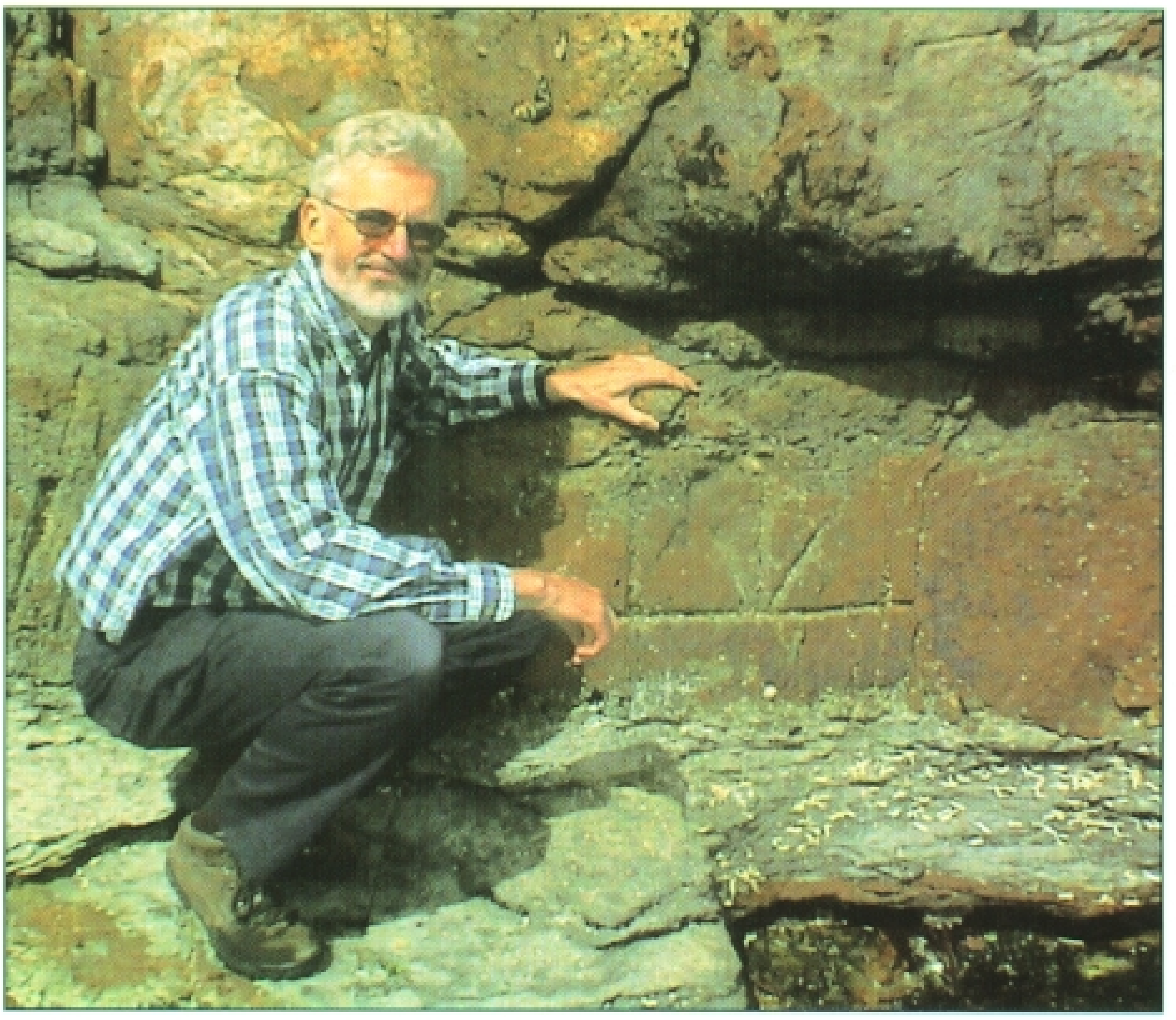

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Cover picture: *John Hunter (Antarctic Cooperative Research Centre, Hobart) at the Isle of the Dead, Port Arthur (Tasmania) sea level benchmark at low tide. The benchmark was inscribed on 1 July 1841, and was one of the first such marks in the world for the scientific investigation of sea level. New information has allowed the mark to be used in estimating sea level change in the region over the past 162 years. The horizontal line in the image is about 0.4 m long.*

For further information, see the Invited Article by John R. Hunter, page 55 of this issue.

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A Whisper from the Past: a Tasmanian Scientific Legacy

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Introduction
One day in October 1995, David Pugh walked into my office in the CSIRO Marine Laboratories in Hobart, setting in train a project that was to become something of an obsession for us for the next seven years. David is a British expert on tides and sea level, the author of a seminal textbook on the subject and one of the founders of the Global Sea Level Observing System (GLOSS). He told me the story of a sea level benchmark struck many years ago on the Isle of the Dead, Port Arthur, Tasmania, at the instigation of three men. One of these was James Clark Ross, the explorer, who wintered in Tasmania in 1841 during his Antarctic expeditions. Ross had been advised by the German geophysicist Baron Von Humboldt to place sea level marks (recording the relative positions of land and sea) during his travels. On arriving in Tasmania, Ross met Sir John Franklin, the Lieutenant Governor, who had a broad interest in science and who had previously been instrumental in the installation of a tide gauge at the nearby penal settlement of Port Arthur in 1837. This gauge was operated by Thomas Lempriere, the Deputy Assistant Commissary General (the storekeeper, an important position within the settlement), who was also an amateur scientist, an accomplished painter and diarist. Lempriere also collected a comprehensive set of meteorological observations at Port Arthur. The coincidence of Ross's visit to Hobart and the existence of a rudimentary tide gauge (*recording* tide gauges probably did not reach Australia until the 1850s), and several years of sea level data, led these men to install a tidal benchmark on the Isle of the Dead, Port Arthur, on 1 July 1841. It is one of the first such marks struck anywhere in the world for the scientific investigation of sea level (see *BAMOS* cover image). This is the story of our study of the scientific legacy left behind by these three men from those early days of the colony.

The Hunt for Lempriere's Data
Since 1841, two people had delved into the sea level observations of Thomas Lempriere. Near the end of the 19th century, Captain Shortt, a naval officer, described the benchmark in a paper to the Royal Society of Tasmania (Shortt, 1889). Unfortunately, Shortt was unable to find any of Lempriere's tidal records, rendering the mark more a feature of general historical interest than a useful indicator of mean sea level. A century later, Bruce Hamon, the eminent CSIRO oceanographer, pursued the subject further (Hamon, 1985), but again was unable to uncover the actual sea level observations. He concluded:
It seems unlikely that interpretation of the bench mark in terms of mean sea level changes can be improved enough to make its re-discovery of real scientific value. . . . The position would of course be different if Lempriere's original observations ever came to light'.

David Pugh left Tasmania a few days after our meeting at CSIRO. We had agreed to search the archives in both Britain and Australia for the tidal data collected by Thomas Lempriere. We corresponded little for the next few months until I received a memorable email from David on 5 January, 1996: '*Good news. Just before Xmas I visited the Royal Society archives in London, and found that they have three years of Lempriere's tidal data from PA, all in his original hand!!*'. The Port Arthur Study was on.

I subsequently (1998) discovered a further year of Lempriere's data at the National Archives of Australia. Interestingly, these had escaped detection for many years by being previously stored, along with some of Lempriere's meteorological data, at the Bureau of Meteorology – not an obvious place in which to look for sea level data.

We now had two pieces of the puzzle: a benchmark on solid rock that has survived to this day, and the existence of several years of sea level observations. A third piece of the puzzle – the relationship between the level of the benchmark and the readings from the tide gauge – was initially provided by Captain

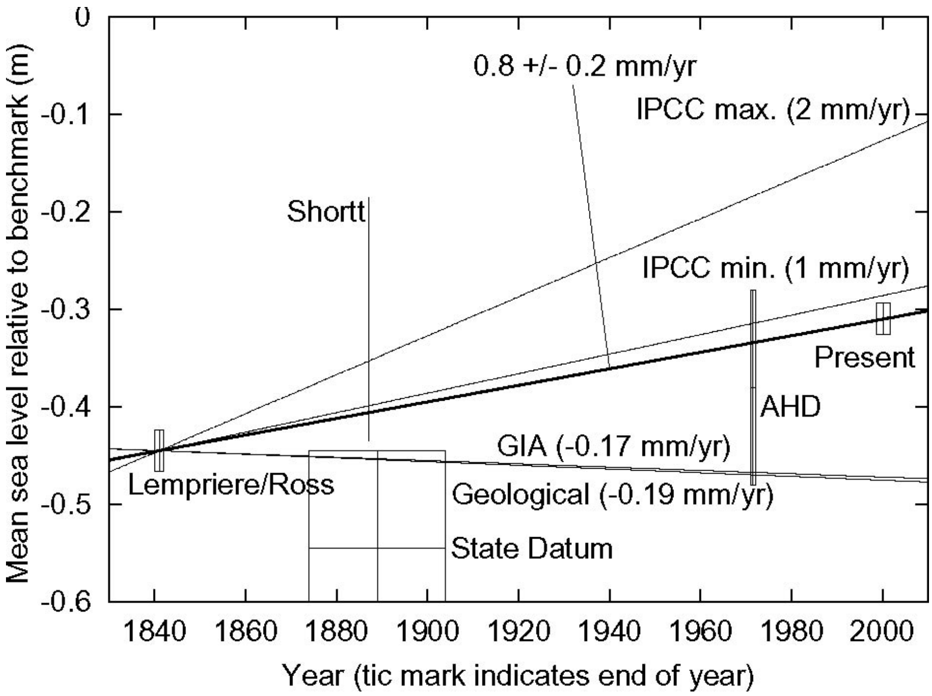

Figure 1 History of sea level estimates at Port Arthur. Each rectangular box represents an estimate of sea level relative to the benchmark; the length of a box shows the duration of the observations and the height provides an estimate of the uncertainty (± one standard deviation). The central slanting (bold) line is our estimate of average sea level rise at Port Arthur, relative to the land; this passes through the best estimates of sea level for 1841-42 and for 1999-2002.

Shortt, who reported the words on a plaque (now lost) that was originally mounted above the mark (Shortt, 1889):
'*On the rock fronting this stone a line denoting the height of the tide now struck on the 1st July, 1841, mean time 4h. 44m. p.m.; moon's age 12 days; height of water in tide gauge 6 ft. 1 in.*'

So the level of the benchmark was equivalent to a reading of 6 ft. 1 in. in Lempriere's gauge. In addition, the plaque indicated the time at which the sea level was at the mark on 1 July 1841, a time which serves as a useful cross-check with the data discovered by David in London. Indeed, the time recorded on the plaque was found to be consistent with the tide gauge records.

With these three pieces of the puzzle, David was able to calculate mean sea level in 1841, relative to the benchmark. The task ahead was now clear: to make new sea level observations at Port Arthur and thereby estimate any change in sea level since 1841. However, what may have seemed a simple task in those heady days in early 1996 soon became a learning experience in the collection of tidal observations, historical research, and many aspects of climate change (including my first introduction to those people who claim that climate change is not even happening).

Problems

One of our first problems was encountered at the end of January 1996, while I was on my first oceanographic voyage to Antarctic waters. I received a fax from Lynette Ross, a Heritage Officer at Port Arthur, with the news of another report of the words on the plaque which accompanied the benchmark. The report was made by a visitor to Port Arthur in 1892, who quoted the words as (*The Australasian*, 1892):
'*On the rock fronting this stone a line, denoting the height of the tide, was struck on the 1st July, 1841. Mean time, 2.44 p.m. Moon's age, 12 days. Height of water in tide gauge, 6ft. 1in.*'.

While this is almost the same as Shortt's quote, it differs by two hours in the time at which sea level was at the benchmark. We put this discrepancy down to a misreading of the plaque (which Captain Shortt noted to be in poor condition) by one of the observers.

Further confusion was introduced by Ross himself, who inferred in his journals that the mark was originally installed at mean sea level

(Ross 1847). However, a comparison of the tidal records and the tide gauge reading noted on the plaque indicate that the mark was installed near the high water mark. We believe that we have resolved this uncertainty by a careful consideration of Lempriere's observations, of tidal hindcasts for that period and of independent Tasmanian estimates of mean sea level since 1841. Our conclusion is that the time noted by Captain Shortt was correct and that Ross was mistaken in stating that the mark was originally at mean sea level.

This uncertainty had one unforeseen consequence. The benchmark today is still near the high water mark. However, if the benchmark was really at mean sea level in 1841, then sea level would have fallen by 0.3 metres since then – a rate of *fall* of about 2 mm/year, in contrast with the present estimate of a *rise* of global mean sea level of 1-2 mm/year (Church et al., 2001). This possibility was quickly taken up by those who call themselves 'greenhouse skeptics' to use as evidence that climate change and sea level rise are not happening (for an alternative interpretation of the Port Arthur story, see: http://www.john-daly.com/).

During the early part of the study it was suggested that, because of natural variability, two years of record in the 1840s would be insufficient for the accurate determination of the change in mean sea level since that time. However, examination of sea level around Australia indicates that the interannual variability in Tasmania is relatively low and almost unaffected by the ENSO cycles that can dominate more northern records. We are extremely lucky that this early sea level mark was installed so far south! After much discussion and the invaluable encouragement of Richard Coleman (University of Tasmania) and John Church (CSIRO Marine Research) it was established that Thomas Lempriere's data would indeed yield a valid estimate of historic mean sea level.

Progress

To determine sea level accurately, you need the help of surveyors in order to relate tide gauge levels to nearby survey marks. In our case we needed to install a tide gauge some distance from the benchmark, across a 1 km stretch of water. David and I had no experience of surveying and so, during 1996 and 1997, we enlisted the help of a number of experienced surveyors. The first of these was Nick Bowden, a State Government surveyor. He was soon joined by Richard Coleman and Peter Morgan (University of Canberra), with Peter securing funding for the tide gauge from his University within a matter of weeks. Subsequently Chris Watson, one of Richard's students, did a splendid job of GPS (Global Positioning System) levelling, and the measurement of waves and seiches at Port Arthur using GPS buoys. The work of these four surveyors was crucial to the success of our study. Richard has been a key member of the project ever since.

In May 1998 a modern acoustic tide gauge was installed at Port Arthur, with the assistance of CSIRO Marine Research (for whom I then worked). Logistic problems delayed the retrieval of good data until August 1999. Since then an almost continuous (99.97% recovery) three years of data have been collected.

The Results

Thomas Lempriere's tide gauge observations consisted of tabulations of times and heights of high and low water. Due to a relocation of his gauge in December 1840 and a consequent change of vertical datum, we were only able to use the years 1841 and 1842. We estimated mean sea level by calculating *mean tide level*, which is just the average of an equal number of high and low water levels, covering the whole record. We calculated mean sea level for our modern data by applying conventional tidal analysis techniques to the three years of record.

Figure 1 summarises the results of our study. Each 'box' on the figure represents the duration and estimated uncertainty of each determination of mean sea level. These estimates of uncertainty are related to: the interannual variability of nearby sea level data, the nodal tide, survey levelling, and instrumental and observational errors. The most important results are those from the historic data of 1841-1842 (marked 'Lempriere/Ross') and from the modern three years of data (marked 'Present'). There are three subsidiary results. The first ('Shortt') is a single observation of sea level made on 24 February 1888, reported by Shortt (1889) and adjusted to represent mean sea level using a tidal hindcast. The second ('State Datum') is derived from the location of the Tasmanian State Datum, which was based on mean sea level for Hobart during 1875-1905, and the third ('AHD') is derived from the Australian Height Datum (Tasmania) which is locally based on mean sea level for Hobart during 1972. The locations of these subsidiary levels confirm that the benchmark could not have been at mean sea level in 1841; if it was, then sea level would have to have fallen steeply (at typically 10 mm/year) prior to 1890, and then risen at around 1 mm/year – we believe this to be physically unrealistic.

We determined the change in mean sea level from the 1840s to modern times using only the 'Lempriere/Ross' and 'Present' results (including the subsidiary results, allowing for the estimated uncertainty of each, makes little difference to the trend). A line passing throughthese two 'primary' results lies within 1.5 standard deviations of the three subsidiary estimates, and yields an average sea level rise relative to the land since the 1840s of 0.8 ± 0.2 mm/year (indicating ± one standard deviation). We have also used two estimates of land uplift at the site (also shown in Figure 2): one from a model of glacial isostatic adjustment or GIA ('GIA' ; Lambeck, 2002) and the other from geological evidence from the past 125,000 years ('Geological'; Banks and Leaman, 1999). From these we have (conservatively) assumed an (upward) vertical motion of the land of 0.2 ± 0.2 mm/year. Adjustment for land uplift yields an estimate of average sea level rise since the 1840s due to an increase in the volume of the ocean of 1.0 ± 0.3 mm/year, which is at the lower end of the rate of global average sea level rise for the 20th century (1-2 mm/year; also shown in Figure 2) given by the Intergovernmental Panel on Climate Change (Church et al., 2001). If it is assumed that most of this sea level rise occurred since about 1890 (the indication from long tidal records from elsewhere; Woodworth, 1999), then the corresponding estimates of rise (1890 to the present) relative to the land, and due to an increase in the volume of the oceans, become 1.2 ± 0.2 mm/year and 1.4 ± 0.3 mm/year, respectively. The estimate of sea level rise due to an increase in the volume of the oceans may be compared with recent estimates for the two longest (continuous) Australian records. Fremantle (32° 30′ S, 115° 44′ E; 91 years to 1996) and Fort Denison (33° 51′ S, 151° 14′ E; 82 years to 1997) showed rates of rise of 1.6 and 1.2 mm/year, respectively, after adjustment for GIA (Lambeck, 2002).

In 1985, Bruce Hamon remarked sadly: 'we must admire the industry and foresight of men like Ross and Lempriere – and regret that so much of Lempriere's effort was in vain' (Hamon, 1985). We are gratified that, in the end, the work of Franklin, Ross and Lempriere, has not been in vain, and that their foresight, long before anyone suspected that there may be such a thing as the greenhouse effect or sea level rise, has provided useful estimates of sea level change in this data-sparse corner of the world.

Further details of the history and science of the Port Arthur benchmark may be found in Pugh et al., 2002, and Hunter et al., 2003.

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