U.S. Geological Survey and The National Academies; USGS OF-2007-1047, Short Research Paper 004; doi:10.3133/of2007-1047.srp004

The Ellsworth Mountains: Critical and enduringly enigmatic

I. W. D. Dalziel

University of Texas Jackson School of Geosciences, Institute for Geophysics, J.J. Pickle Research Campus, 10100 Burnet Rd. Building 196 (R2200), Austin, TX 78758 (ian@ig.utexas.edu)

Abstract The Ellsworth Mountains, first mapped under the leadership of Campbell Craddock, pose critical geological enigmas, solved and unsolved. The isolation of the mountains, their abrupt structural terminations and Paleozoic stratigraphic affinities are explained by rotation from the cratonic margin during Gondwanaland breakup. The mechanism remains obscure. The absence of intense folding associated with the Cambro-Ordovician Ross orogeny can be ascribed to local extension along a subducting margin. Yet tantalizing questions regarding possible Precambrian connections to Laurentia remain, and the cause of the post-Permian Gondwanide folding is controversial.

The elevation (~5000m) is high for an early Mesozoic fold belt. Thermal uplift could have been initiated during Jurassic-Cretaceous block rotation and Weddell Sea opening and continued into the Cenozoic. The history of glaciation provides input for models of ice loading and unloading. Measurements of present-day uplift test these models and help assess change in the mass of the ice sheet and hence in global sea level.

Citation: Dalziel, I.W.D., (2007), The Ellsworth Mountains: Critical and Enduringly Enigmatic, in Antarctica: A Keystone in a Changing World – Online Proceedings of the 10th ISAES, edited by A. K. Cooper and C. R. Raymond et al., USGS Open-File Report 2007-1047, Short Research Paper 004, 5 p.; doi:10.3133/of2007-1047.srp004.

Introduction

The rugged and starkly beautiful Ellsworth Mountains at the head of the Weddell Sea embayment (Fig. 1) include the highest peak on the Antarctic continent, the Vinson Massif (4892m). The mountains were discovered by Lincoln Ellsworth during a 1935 flight from the Antarctic Peninsula to the Ross Ice Shelf, and first visited during the International Geophysical Year in the course of an oversnow traverse led by Charles R. Bentley of the University of Wisconsin. The first detailed geologic mapping, during the 1960's, was undertaken by field parties from the University of Minnesota led by Campbell Craddock. Some of the subsequent work by large helicopter-supported interdisciplinary teams were also led by him. It is Cam Craddock's pioneering work in the Ellsworth's that is being celebrated in this special session in his honor at the Xth International Symposium on Antarctic Earth Sciences.

This introductory contribution is intended to put the Ellsworth Mountains in the context of the Antarctic continent, of the Gondwanaland supercontinent and indeed of global paleogeography and Earth evolution. This may sound grandiose for a comparatively small, remote, and isolated mountain range, no matter how majestic. Nonetheless the geology of the Ellsworths first elucidated by Craddock and his colleagues does resonate on a global scale and through at least a billion years of time. It even has a bearing on the future through estimates of past ice mass and measurements of post-glacial rebound.

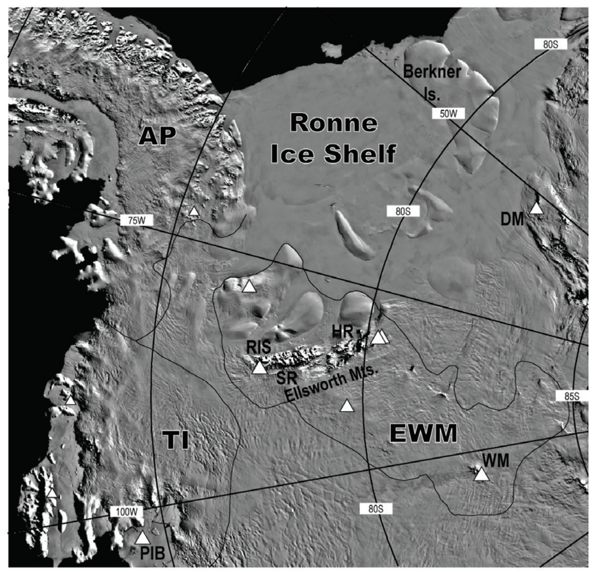

Figure 1. Geographic and tectonic setting of the Ellsworth Mountains. Crustal blocks of West Antarctica: AP–Antarctic Peninsula; EWM–Ellsworth-Whitmore; TI–Thurston Island-Eights Coast; DM–Dufek Massif; HR–Heritage Range; PIB–Pine Island Bay; RIS–Rutford Ice Stream; SR–Sentinel Range; WM–Whitmore Mountains White triangles–GPS stations of the WAGN network (see text).

Origin

The discovery of the isolated Ellsworth Mountains posed an immediate geological enigma given the fact that they are composed mainly of intensely folded Paleozoic sedimentary strata (Craddock et al., 1964; Craddock, 1969; Webers et al., 1992a). Why do they terminate so abruptly along strike both in the north and the south? Their geology is unlike that of all other parts of West Antarctica but comparable to that of the Trans-antarctic Mountains, from which they are separated by almost five degrees of latitude. Why?

The late James Schopf, a paleobotanist, pioneered the route to the solution of these enigmas nearly forty years ago when he suggested, after listening to a lecture on seafloor spreading by the Canadian geophysicist J. Tuzo Wilson, that the Ellsworths are a displaced fragment of the Transantarctic margin of the East Antarctic craton (Schopf, 1969). Geologic and paleomagnetic studies over the past quarter century have supported his hypothesis (Fig. 2; Watts and Bramall, 1981; Dalziel and Elliot, 1982; Grunow et al., 1987; Dalziel and Grunow, 1992; Dalziel, 1997; Curtis, 2001; Randall and Mac Niocaill, 2004), but immediately highlighted a fresh enigma. How was this cratonic fragment moved? Schopf had suggested seafloor spreading as a mechanism, yet seismic reflection profiling in the Weddell Sea basin has revealed no disturbance of its Mesozoic and Cenozoic basin fill that surely would have accompanied its passage (Huebscher et al., 1996).

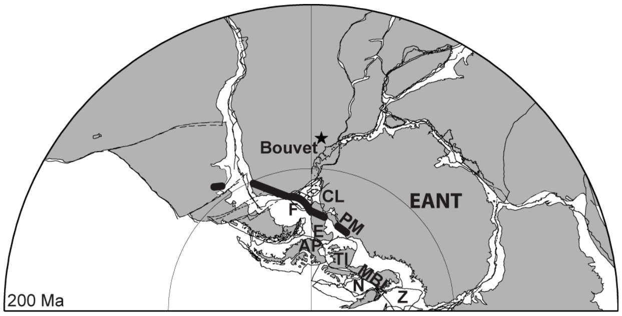

Figure 2. Latest Triassic Gondwanaland. Crustal blocks: CL–Coats Land; E–Ellsworth-Whitmore; EANT–East Antarctic craton; F–Falkland Islands; MBL–Marie Byrd Land; NZ–New Zealand; PM–Pensacola Mountains (for AP, EWM, TI see Fig. 1) star–relative position of present-day Bouvet hot spot; thick line–Gondwanide fold belt.

My colleagues and I have suggested that the motion took place during crustal stretching that resulted in the formation of the basin, thus predating deposition of the basinal sediments (Fig. 3; Dalziel and Lawver, 2001; Dalziel et al., 2000). The process, we suggest, was analogous to the recent rotation of the Dannakil horst of northeastern Africa due to stretching and igneous intrusion within the Afar triangle. Identical stretching and rotation occurred on the formerly adjacent South American margin of the Southern Ocean, where the Falkland Islands block rotated during formation of sedimentary basins on the Falkland Plateau prior to opening of the South Atlantic Ocean basin.

Early Paleozoic Paleogeography

The stratigraphy and structure of the strata forming the Ellsworth Mountains are also enigmatic. Why do they show no clear evidence of the early Paleozoic Ross-Delamerian orogenic deformation that occurred along the rest of the Transantarctic and the eastern Australian margins of Gondwanaland? Instead, the strata record almost continuous sedimentation from Early Cambrian to Permian times. It appears that all the folding and cleavage development in the Paleozoic strata occurred after the deposition of the youngest *Glossopteris*-bearing Permian strata of the Polar Star Formation as part of the latest Paleozoic to early Mesozoic Gondwanide orogeny. Curtis (2001) suggests that Cambrian rift-related magmatism reflects extension due to local back-arc or slab-capture tectonics along the subducting Pacific margin of Gondwanaland. I had suggested earlier that a promontory of Laurentia that I named the Texas Plateau could have rifted from this part of the Gondwanaland margin at the end of the Precambrian (Dalziel, 1997). Curtis believes that rift-drift transition in the Cape embayment in the Gondwanaland margin was too young, Middle to Late Cambrian, for this to be true given the Precambrian-Cambrian boundary age of rift-drift transition along the proto-Appalachian margin.

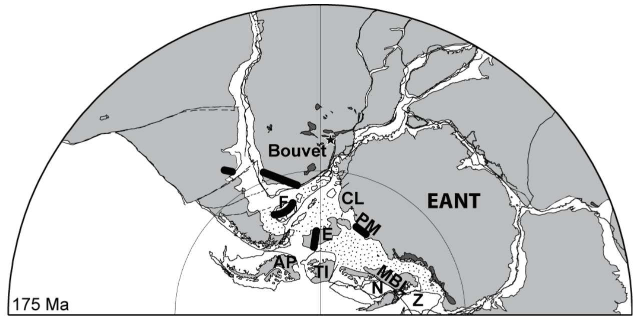

Figure 3. Early-Middle Jurassic Gondwanaland. Crustal blocks as in Figs. 1 and 2, dark gray–Ferrar (Antarctica) and Karroo (Africa) large igneous province; stippled areas–extended continental crust

Nonetheless, tantalizing clues that Laurentia might have separated from West Gondwanaland at the end of the Precambrian remain unexplained. Most notably, the undeformed ~1100 Ma felsic igneous rocks of Coats Land, adjacent to the original position of the Ellsworths (Fig. 2), contain Pb-isotopes characteristic of the contemporaneous Keeweenawan igneous rocks of Laurentia rather than of those of the Umkondo province of the Kalahari craton (S. Loewy, R. Hanson, and I. Dalziel, unpublished data). Also, the trilobite and, especially, primitive molluscan faunas of the Cambrian strata of the Ellsworths bear resemblance to those of North America (Jago and Webers, 1992; Webers et al., 1992b). With separation of Laurentia and Gondwanaland about a pole of rotation near the Cape of Good Hope embayment, this would be possible. Paleomagnetic data from the Coats Land rocks (Gose et al., 1997) are compatible with a position of Coats Land adjacent to the present southern margin of Laurentia at ~1100 Ma (Jacobs et al., in press).

Gondwanide Deformation

Reconstruction of the Ellsworth Mountains and Falkland Islands blocks along the Gondwanaland margin using paleomagnetic data confirms the continuity of the late Paleozoic–early Mesozoic Gondwanide fold belt first recognized by Du Toit (1937) as extending from the Sierra de la Ventana in Argentina through the Cape Mountains of southern Africa, and predicted by him to extend into Antarctica where it has subsequently been recognized in the Pensacola Mountains (Fig. 2.). The enigmatic aspects of this fold belt are its limited extent along strike in relation to the length of the Pacific margin of Gondwanaland, and its distance, ~1500 km, from that margin on a reconstruction. It has hence been variously ascribed to 'flat-slab' subduction as in the Central Andes of today, or to the collision of an exotic terrane with the Gondwanaland subducting margin. There is, however, no exotic terrane larger than a fusulinid-covered seamount outboard of the Gondwanide fold belt.

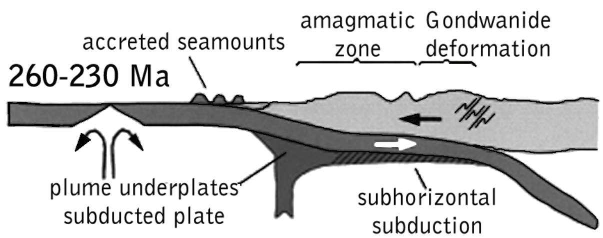

Figure 4. Postulated relationship of mantle plume source of subsequent 185-180 Ma Ferrar-Karroo large igneous province and Gondwanide fold belt (Dalziel et al., 2000; see text).

The near coincidence in time and space of the Gondwanide deformation, the Karooo-Ferrar large igneous province (LIP) and the initial fragmentation of Gondwanaland in the southwest Indian Ocean basin region have been remarked on by many authors over the years. Seeking to explain this coincidence, and the origin of the Gondwanide fold belt itself, my colleagues and I have suggested that a flat slab resulting in transmission of frictional stress in the upper plate well into the supercontinental interior could have occurred as a result either of Gondwanaland overriding a mantle plume, or a rising plume first impinging on the slab as it was being subducted along a segment of the margin (Fig. 4; Dalziel et al., 2000). The deformation could thus have been followed by the plume thermo-mechanically penetrating the slab and erupting as the Karoo-Ferrar LIP. In turn, the stress field generated by the rising plume on the super-continental lithosphere could have resulted in the initial break leading to ocean basin formation. Granitic plutons of Jurassic age form the Whitmore Mountains and smaller nunataks of the Ellsworth-Whitmore mountains crustal block (Craddock, 1972). Some appear to be differentiates of a Ferrar magma, others may be crustal melts (Storey et al., 1988).

Mesozoic-Cenozoic uplift of the Ellsworth Mountains

The elevation of the Ellsworth Mountains is twice that of the Cape Mountains of southern Africa and over three time that of the Sierra de La Ventana of Argentina. The relief between the Vinson Massif and the bottom of the basin filled by the adjacent Rutford Ice Stream is ~7000m, equivalent to that between Nanga Parbat and the floor of the Indus Gorge in the Himalayas. The Vinson Massif is located in the northern Sentinel Range of the Ellsworths, which is significantly higher than the Heritage Range in the south. The higher elevation of the Sentinels appears to be at least in part the result of the preservation of the weathering-resistant Crashsite Quartzite, which has been eroded from above the older rocks of the Heritage Range within a north-plunging anticlinorium. The two ranges lie along the Weddell Sea margin of the Ellsworth-Whitmore crustal block, and the interior parts of the block are comparatively low lying.

Apatite fission-track analysis of samples covering a 4200m vertical section on the western side of the Vinson Massif indicates uplift of 4 km or more in the Early Cretaceous during the initial separation of East and West Gondwanaland and accompanying opening of the Weddell Sea (Fitzgerald and Stump, 1991). The fission track studies further demonstrate that relief of at least 1.8 km has persisted since the Early Cretaceous, and that a maximum of 3 km of uplift has occurred since that time. This means that a significant part of the relief of the Ellsworth Mountains existed prior to the Neogene. It is therefore not likely to be the result of formation of the active West Antarctic Rift System (WARS) that is most prominent in the Ross Sea embayment. Indeed, it is not clear how far the WARS extends inland from the Ross Sea, nor whether it terminates inland or extends north of the Ellsworths into either the Amundsen Sea or Weddell Sea basins (Dalziel, 2006). The mountains closely parallel the Rutford Ice Stream. This trough, Carlson Inlet, the Evans Ice Stream and intervening Fletcher Promontory and Fowler Peninsula form a graben and horst topography indicating rifting, but the age of this event is unknown.

Glacial History and the Future

The tectonic history of the Ellsworth-Whitmore mountains crustal block of West Antarctica has played a major role in the initiation and development of the West Antarctic Ice Sheet. The Ellsworths form a mountain barrier between the Weddell and Ross embayments, without which, it can be argued, the West Antarctic Ice Sheet might not exist (Dalziel and Lawver, 2001). They constitute a 'dipstick' that records the changing thickness of the ice sheet. With the advent of cosmogenic isotope surface exposure dating, we now have a tool to determine the age of earlier ice levels. This is significant not only with regard to the glacial history and changing mass of the ice sheet, but also with regard to modelling of post-glacial rebound since the last glacial maximum, and hence assessment of any change in mass of the ice sheet and consequent predictions of global sea level change.

Figure 5. Glacial trimline on ridge of Mt. Epperly, Sentinel Range (courtesy of Mike Bentley; see text).

Of particular note is the existence of a marked 'trimline' reflecting a former ice sheet level (Fig. 5; Denton et al., 1992). Below this elevation there is alpine topography with smoothed and striated ridge crests, above the ridges are serrated. On the western side of the Sentinel Range, the trim line varies in elevation from ~2000-3000m. On the eastern side it is located at 2000-2680m. The elevation of the trimline in the Heritage Range is lower, 1700–2400m. This 'dipstick' for the former elevation of the ice sheet is, together with the former position of the grounding line of the ice sheet on the continental shelf, a major input to the ice sheet loading and unloading models used to predict the present rate of post-glacial rebound of the crust.

The age of the trimline, however, is currently being studied using cosmogenic isotopes that measure the age of exposure of the bedrock. This age was estimated by Denton et al. (1992) as either late Wisconsinan (i.e., last glacial) or pre-late Quaternary They recognized the possibility of the glacial features of the Ellsworths representing more than one glaciation. Recent work by Mike Bentley and his colleagues at the universities of Durham and Edinburgh has yielded preliminary ages for the exposure of rock outcrops in the Ellsworths that indicate a complex glacial history ranging from the pre-Quaternary to the present (M. Bentley, personal communication, 2007).

The ice sheet models use the glacial geology as the basis for estimates of the extent of the ice sheet during the last glacial maximum and an assumed mantle rheology to calculate the present-day post-glacial rebound. They may therefore be unreliable in calculating the change in the mass of the West Antarctic Ice Sheet by repeat satellite measurements of ice surface elevation and gravity (Thomas et al., 2004; Velicogna and Wahr, 2006). As these calculations are totally dependent on the value of the post-glacial rebound correction, direct measurements of the change in bedrock elevation are required.

The Ellsworth Mountains are a critical location for these measurements, precisely because the estimates of the former extent of the ice sheet have been made there. Together with my colleagues in the University of Memphis (Robert Smalley), the Ohio State University (Michael Bevis and Eric Kendrick), and the University of Texas at Austin (Fred Taylor), I have spent several seasons installing a Global Positioning System network on bedrock nunataks throughout West Antarctica in part to measure this postglacial rebound directly. Our West Antarctic GPS Network (WAGN) includes several bedrock sites (6) on the Ellsworth-Whitmore mountains crustal block and one at the base of the Antarctic Peninsula (Fig. 1). Although our measurements will need to be augmented with continuously recorded data in the future, we hope that we will soon have data that records the rate of post-glacial rebound at the present time, and will lead to a better evaluation of the meaning of the ice surface elevation and gravity data with regard to ice mass and hence sea level change.

Discussion

The original geological mapping of the Ellsworth Mountains under the leadership of Campbell Craddock has provided a sound basis for a wide spectrum of studies ranging from global paleogeography in late Precambrian times to the history of Cenozoic glaciation and present-day uplift. Some of the originally puzzling aspects of the geology have been elucidated, such as the isolation and abrupt terminations of the mountains and their stratigraphic affinities with East Antarctica. Other enigmas such as the late Precambrian paleogeography and the tectonic mechanism of early Mesozoic deformation remain for geologists of the future to investigate. Several aspects of the geology of the Ellsworths are critical in understanding earth history and processes far beyond these lonely ranges. None more so than, the history of glaciation and neotectonics, which have a direct bearing on assessments of ice mass and sea level change and hence our understanding of the future of the planet.

Acknowledgements. I thank Mike Bentley, John Craddock, and Wesley LeMasurier for criticisms and suggestions that markedly improved the manuscript.

References

Craddock, C., (1969), Geology of the Ellsworth Mountains, edited by Bushnell, V. C., and Craddock, C., Geologic Maps of Antarctica, Antarctic Map Folio Series, Folio 12, Plate IV: New York, American Geographical Society, p. Sheet 4.

Craddock, C., (1972), Antarctic tectonics: edited by Adie, R.J., Antarctic Geology and Geophysics, Oslo, Universitetsforlaget, p. 449-455.

Craddock, C., Anderson, J. J., and Webers, G. F., (1964), Geologic outline of the Ellsworth Mountains, edited by Adie, R. J., Proceedings of First International Symposium on Antarctic Geology: Cape Town, North-Holland, p. 155-170.

Curtis, M. L., (2001), Tectonic history of the Ellsworth Mountains, West Antarctica; reconciling a Gondwana enigma: Geological Society of America Bulletin, v. 113, p. 939-958.

Dalziel, I. W. D., (1997), Neoproterozoic-Paleozoic geography and tectonics: Review, hypothesis, environmental speculation: Bull. Geol. Soc. Am., v. 109, p. 16-42.

—, (2006), On the extent of the active West Antarctic rift system, edited by Siddoway, C. S., and Ricci, C. A., Proceedings of Workshop on Frontiers and Opportunities in Antarctic Geosciences, Terra Antarctica Reports No. 12: Sienna, Italy, Terra Antarctica Publi-cations, p. 193-202.

Dalziel, I. W. D., and Elliot, D. H., (1982), West Antarctica: Problem child of Gondwanaland: Tectonics, v. 1, p. 3-19.

Dalziel, I. W. D., and Grunow, A. M., (1992), Late Gondwanide tectonic rotations within Gondwanaland: Causes and consequences: Tectonics, v. 11, p. 603-606.

Dalziel, I. W. D., and Lawver, L. A., (2001), The lithospheric setting of the West Antarctic Ice Sheet, edited by Alley, R. B., and Bindschadler, R. A., The West Antarctic Ice Sheet: Behavior and Environment, Volume 77: Antarctic Research Series: Washington, DC, American Geophysical Union, p. 29-44.

Dalziel, I. W. D., Lawver, L. A., and Murphy, J. B., (2000), Plumes, orogenesis, and supercontinental fragmentation: Earth Planet. Sci. Lett., v. 178, p. 1-11.

Denton, G. H., Bockheim, J. G., Rutford, R. H., and Andersen, B. G., (1992), Glacial history of the Ellsworth Mountains, West Antarctica, edited by Webers, G. F., Craddock, C., and Splettstoesser, J. F., Geological Society of America Memoir No. 170: Boulder, CO, Geological Society of America (GSA), p. 403-432.

DuToit, A. L., (1937), Our Wandering Continents: Edinburgh, Scotland, Oliver and Boyd, 355 p.

Fitzgerald, P. G., and Stump, E., (1991), Early Cretaceous uplift in the Ellsworth Mountains of West Antarctica: Science, v. 92-94, p. 254.

Gose, W. A., Helper, M. A., Connelly, J. N., Hutson, F. E., and Dalziel, I. W. D., (1997), Paleomagnetic data and U-Pb isotopic ages from Coats Land, Antarctica: Implications for Neoproterozoic plate reconstructions: Journal of Geophysical Research, v. 102, p. 7887-7902.

Grunow, A. M., Dalziel, I. W. D., and Kent, D. V., (1987), Ellsworth-Whitmore mountains crustal block, Western Antarctica: New paleomagnetic results and their tectonic significance, edited by McKenzie, G. D., Gondwana Six: Structure, Tectonics and Geophysics, Volume 40: Geophysical Monograph Series: Washington, DC, American Geophysical Union, p. 161-172.

Huebscher, C., Jokat, W., and Miller, H., (1996), Structure and origin of southern Weddell Sea crust; results and implications, edited by Storey, B. C., King, E. C., and Livermore, R. A., Weddell Sea tectonics and Gondwana break-up: Geological Society Special Publications: London, Geological Society of London, p. 201-211.

Jacobs, J., Pisarevsky, S. A., Thomas, R. J., and Becker, T., (in press (2007)), The Kalahari Craton during the assembly and dispersal of Rodinia, Precambrian Research.

Jago, J. B., and Webers, G. F., (1992), Middle Cambrian trilobites from the Ellsworth Mountains, West Antarctica, edited by Webers, G. F., Craddock, C., and Splettstoesser, J. F., Geology and paleontology of the Ellsworth Mountains, West Antarctica: Geological Society of America Memoir No. 170: Boulder, CO, Geological Society of America (GSA), p. 101-124.

Randall, D. E., and Mac Niocaill, C., (2004), Cambrian palaeomagnetic data confirm a Natal embayment location for the Ellsworth-Whitmore Mountains, Antarctica, in Gondwana reconstructions: Geophysical Journal International, v. 157, p. 105-116.

Schopf, J. M., (1969), Ellsworth Mountains: Position in West Antarctica due to sea-floor spreading: Science, v. 164, p. 63-66.

Storey, B.C., Hole, M.J., Pankhurst, R.J., Miller, I.L., and Vennum, W. (1988), Middle Jurassic within-plate granites in West Antarctica and their bearing on the break-up of Gondwanaland: Journal of the Geological Society of London, v. 145, p. 999-1007.

Thomas, R., Rignot, E., Casassa, G., Kanagaratnam, P., Acuna, C., Akins, T., Brecher, H., Frederick, E., Gogineni, P., Krabill, W., Manizade, S., Ramamoorthy, H., Rivera, A., Russell, R., Sonntag, J., Swift, R., Yungel, J., and Zwally, J., (2004), Accelerated sea-level rise from West Antarctica: Science, v. 306, p. 255-258.

Velicogna, I., and Wahr, J., (2006), Measurements of time-variable gravity show mass loss in Antarctica: Science, v. 311, p. 1754-1756.

Watts, D. R., and Bramall, A. M., (1981), Paleomagnetic evidence for a displaced terrain in western Antarctica: Nature, v. 293, p. 638-641.

Webers, G. F., Craddock, C., and Splettstoesser, J. F., (1992a), Geologic history of the Ellsworth Mountains, Antarctica, Geological Society of America Memoir No. 170: Boulder, CO, Geological Society of America (GSA), p. 181-248.

Webers, G. F., Pojeta, J., and Yochelson, E. L., (1992b), Cambrian Mollusca from the Minaret Formation, Ellsworth Mountains, West Antarctica, edited by Webers, G. F., Craddock, C., and Splettstoesser, J. F., Geology and Paleontology of the Ellsworth Mountains, West Antarctica: Boulder, CO, Geological Society of America (GSA), p. 181-248.