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Education

Ph.D., Mineral Economics, The Pennsylvania State University, 1983.
M.S., Geochemistry and Mineralogy, The Pennsylvania State University, 1980.
B.A., Earth Sciences, Dartmouth College, 1978.

Current Employment

1986-present Colorado School of Mines, Division of Economics and Business (prior to 1994, the Mineral Economics Department). Starting in 2013, Deputy Director of the Critical Materials Institute, an Energy Innovation Hub of the U.S. Department of Energy.

Positions: Interim Division Director, 2017-present; Professor, 1996-present; Division Director, 1998-2013; Associate Professor, 1989-1996; Assistant Professor, 1986-1989.

Academic Areas of Specialization: mineral economics, natural resource and environmental economics, applied microeconomics.

Research Interests: mineral exploration; mining, minerals, and sustainable development; mineral policy; mineral and metal markets.

Thesis Advising: advisor or co-advisor for 19 M.S. and 18 Ph.D. theses.

Courses Taught:

Undergraduate

Business Strategy
Field Session (undergraduate research)
Macroeconomics (Principles, Intermediate)
Microeconomics (Principles, Intermediate)

Graduate

Econometrics
Economics and Decision Making
Energy Economics
Environmental Economics
Exploration Economics
Macroeconomics
Metal Industries and Markets
Natural Resource Economics

Representative University Service: Faculty Handbook Committee, McBride Honors Program Executive Committee, Research Management Cabinet, Strategic Planning Committee, various search committees.

Previous Employment

- 1985-1986 Assistant Professor (visiting), Mineral Economics Department, The Pennsylvania State University.
- 1984-1985 Visiting Scholar, Energy and Materials Division, Resources for the Future, Washington, D.C.
- 1982-1984 Research Scholar, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Other Professional Experience and Awards

- 2017-now Member, Royalty Policy Committee, advisory to the Secretary of the U.S. Department of the Interior.
- 2017 Testified at the public hearing to examine the United States' increasing dependence on foreign sources of minerals and opportunities to rebuild and improve the supply chain in the United States, Committee on Energy and Natural Resources, U.S. Senate, March 28, 2017.
- 2015-2016 Member, study committee established by the American Physical Society (APS), the Materials Research Society (MRS) and the American Chemical Society (ACS) to evaluate the economic viability of transitioning academic users of helium from open, venting helium systems to closed-loop systems that recycle helium. Committee report published as Responding to the U.S. Research Community's Liquid Helium Crisis (APS, MRS and ACS, 2016).
- 2014 Testified at the public hearing on S. 1600, The Critical Minerals Policy Act of 2013, Committee on Energy and Natural Resources, U.S. Senate, January 28, 2014.
- 2011 Testified at the public hearing on "Strategic and Critical Minerals Policy: Domestic Minerals Supplies and Demands in a Time of Foreign Supply Disruptions," Subcommittee on Energy and Mineral Resources, Committee on Natural Resources, U.S. House of Representatives, Washington, D.C., May 24, 2011.
- 2011 Testified at the public hearing on "An Effective Raw Materials Strategy for Europe," Committee on Industry, Research and Energy, European Parliament, Brussels, Belgium, January 26.

- 2010 Testified at the public hearing on “The Role of Strategic Minerals in Clean Energy Technologies and Other Applications,” Subcommittee on Energy, Committee on Energy and Natural Resources, U.S. Senate, Washington, D.C., September 30.
- 2010-2011 Member, study committee established by the American Physical Society (APS) and the Materials Research Society (MRS). Committee report published as Energy Critical Elements: Securing Materials for Emerging Technologies (APS and MRS, 2011).
- 2010 Recipient, 2010 Mineral Economics Award of the American Institute of Mining, Metallurgical, and Petroleum Engineers.
- 2006-2008 Chair, Committee on Critical Mineral Impacts on the U.S. Economy, review panel of the Board on Earth Sciences and Resources, U.S. National Research Council. Committee report published as Minerals, Critical Minerals, and the U.S. Economy (Washington, D.C., National Academies Press, 2008).
- 2003-2007 Member, Advisory Committee of the Mineral Economics Research Program, Catholic University of Chile.
- 1988-2006 Editor, Resources Policy, an international journal of mineral economics and policy published by Elsevier Science (Oxford, UK).
- 2002-2003 Member, Committee to Review the U.S. Geological Survey’s Mineral Resources Program, organized under the auspices of the National Research Council. Committee report published as Future Challenges for the U.S. Geological Survey’s Mineral Resources Program (Washington, D.C., National Academies Press, 2003).
- 2002 Recipient of the Mineral Economics and Management Society Award.
- 2001-2002 Member of the Board, Mineral Economics and Management Society.
- 1993-1998 Member, Committee on Earth Resources, a committee of the Board on Earth Sciences and Resources, U.S. National Research Council.
- 1996-1997 President, Mineral Economics and Management Society.
- 1996 Centennial Fellow, College of Earth and Mineral Sciences, Pennsylvania State University.
- 1995-1996 Member, Panel to Review the Mineral Resource Surveys Program Plan of the U.S. Geological Survey, under the auspices of the U.S. National Research Council. Panel report published as Mineral Resources and Society: A Review of

the Program Plan of the U.S. Geological Survey's Mineral Resource Surveys Program (Washington, D.C., National Academy Press, 1996).

Recent years Visiting academic appointments at University of the Witwatersrand (sabbatical leave, October-December 2007); Catholic University of Chile (sabbatical leave, March-May 2008); and Curtin University and the University of Chile (various years, 1994-present), where I have taught short, intensive courses on mineral economics.

Consulting projects (paid and pro bono) for various organizations including: First Solar; International Monetary Fund; the Keystone Center; Japan Oil, Gas, and Metals National Corporation; United Nations Conference on Trade and Development; United Nations Development Programme; Wiley Rein; World Bank.

Books

Mining and the Environment: International Perspectives on Public Policy (Washington, D.C.: Resources for the Future, 1994). Editor.

International Mineral Economics: Mineral Exploration, Mine Valuation, Markets, and International Mineral Policies (Berlin: Springer-Verlag, 1988). Co-authored with Werner Gocht and Half Zantop.

World Mineral Exploration: Trends and Economic Issues (Washington, D.C.: Resources for the Future, 1988). Co-edited with John E. Tilton and Hans H. Landsberg.

Metallic Mineral Exploration: An Economic Analysis (Washington, D.C.: Resources for the Future, 1987).

Journal Articles and Book Chapters

“Public policy and future mineral supplies,” Resources Policy, 2018. DOI: <https://doi.org/10.1016/j.resourpol.2018.01.006>. Co-authored with J.E. Tilton, P.C.F. Crowson, J.H. DeYoung Jr., M. Ericsson, J.I. Guzman, D. Humphreys, G. Lagos, P. Maxwell, M. Radetzki, D.A. Singer and F.W. Wellmer.

“Market Analysis for Mineral Property Feasibility Studies,” chapter 8, pp. 209-230 in Richard L. Bullock and Scott Mernitz, editors, Mineral Property Evaluation: Handbook for Feasibility Studies and Due Diligence (Englewood, Colorado, USA, Society for Mining, Metallurgy & Exploration, 2018).

“Simulating producer responses to selected Chinese rare earth policies,” Resources Policy, 2017. DOI: <https://dx.doe.org/10.1016/j.resourpol.2017.10.013>. Co-authored with Maxwell Brown.

“Materials, critical materials and clean-energy technologies,” EPJ Web of Conferences, volume 148, 2017, in D. Cahen, L. Cifarelli, D. Ginley, A. Slaoui, A. Terrasai and F. Wagner, editors, 5th

course of the MRS-EMRS “Materials for Energy and Sustainability” and 3rd course of the “EPS-SIF International School of Energy.” DOI: <https://doi.org/10.1051/epjconf/201714800003>.

“The Rare Earths as Critical Materials,” pp. 19-46 in Jean-Claude Bünzli and Vitalij Pecharsky, editors, Handbook on the Physics and Chemistry of Rare Earths, volume 50 (Amsterdam, Elsevier, 2016). Co-authored with A.H. King and K.J. Gschneidner Jr.

“Rare earths: market disruption, innovation, and global supply chains,” Annual Review of Environment and Resources, 2016. DOI:10.1146/annurev-environ-110615-085700. Co-authored with Cyrus Wadia, Corby Anderson, Diana Bauer, Fletcher Fields, Lawrence Meinert and Patrick Taylor.

“Economic Perspectives on Sustainability, Mineral Development, and Metal Life Cycles,” pp. 467-484 in Reed M. Izatt, editor, Metal Sustainability: Global Challenges, Consequences, and Prospects (New York, Wiley & Sons, 2016).

“Potential uranium supply from phosphoric acid: A U.S. analysis comparing solvent extraction and ion exchange recovery,” Resources Policy, 2016. DOI:10.1016/j.resourpol.2016.06.004. Co-authored with Hayeon Kim, Brett W. Carlsen and Brent Dixon.

“The present and future silver cost component in crystalline silicon PV module manufacturing,” Photovoltaics International, March 2016, vol. 31, pp. 41-52. Co-authored with Michael Redlinger and Michael Woodhouse.

“Antworten auf die Kritikalität von Materialien: Historische Beispiele” [“Responding to Material Criticality: Historical Examples”], pp. 29-35 in P. Kausch, J. Matschullat, M. Bertau and H. Mischo, editors, Rohstoffwirtschaft und gesellschaftliche Entwicklung [The Raw Materials Industry and Development] (Berlin, Springer Spektrum, 2016).

“Multifaceted material substitution: The case of NdFeB magnets, 2010-2015,” JOM, 2016. DOI:10.1007/s11837-016-1913-2. Co-authored with Braeton E. Smith.

“Volatility of by-product metal and mineral prices,” Resources Policy, vol 47, March 2016, pp. 69-77. DOI:10.1016/j.resourpol.2015.12.002. Co-authored with Michael Redlinger.

“Evaluating the Availability of Gallium, Indium, and Tellurium from Recycled Photovoltaic Modules,” Solar Energy Materials and Solar Cells, vol. 138, July 2015, pp. 58-71. DOI: 10.1016/j.solmat.2015.02.027. Co-authored with Michael Redlinger and Michael Woodhouse.

“Thorium: Crustal Abundance, Joint Production, and Economic Availability,” Resources Policy, 2015, pp. 81-93. DOI: 10.1016/j.resourpol.2015.02.002. Co-authored with Brett W. Jordan, Brent W. Dixon, and Brett W. Carlsen.

“A market-clearing model of the uranium and enrichment industries,” Nuclear Technology, 2013, vol. 183, no. 2, pp. 160-177. Co-authored with E.A. Schneider, U.B. Phathanapirom, and E. Segal.

“Perspectives on Pathways for Cadmium Telluride Photovoltaic Module Manufacturers to Address Expected Increases in the Price of Tellurium,” Solar Energy Materials and Solar Cells, vol. 115, August 2013, pp. 199-212. DOI: 10.1016/j.solmat.2012.03.023. Co-authored with M. Woodhouse, A. Goodrich, R. Margolis, T. James, R. Dhere, T. Gessert, T. Barnes, and D. Albin.

“Mining, Sustainability, and Sustainable Development,” in Philip Maxwell, editor, Australian Mineral Economics, Monograph 24 (Carlton, Victoria, Australia, Australasian Institute of Mining and Metallurgy, 2013). Updated and revised version of 2006 book.

“Supply-Chain Dynamics of Tellurium, Indium, and Gallium Within the Context of PV Manufacturing Costs,” IEEE Journal of Photovoltaics, vol. 3, no. 2, April 2013, pp. 833-837. DOI: 10.1109/JPHOTOV.2013.2242960. Co-authored with M. Woodhouse, A. Goodrich, R. Margolis, T.L. James, and M. Lokanc.

“Deep-Sea Mining of Seafloor Massive Sulfides,” Marine Policy, vol. 34, 2010, pp. 728-732. Co-authored with P. Hoagland, S. Beaulieu, M.A. Tivey, C. German, L. Glowka, and J. Lin.

“What Sustainability and Sustainable Development Mean for Mining,” pp. 19-32 in J. A. Botin, editor, Sustainable Management of Mining Operations (Littleton, Colorado, Society of Mining, Metallurgy, and Exploration, 2009).

“Depletion and the Future Availability of Petroleum Resources,” The Energy Journal, vol. 30, no. 1, 2009, pp. 141-174. Co-authored with Roberto Aguilera, Gustavo Lagos, and John E. Tilton.

“The Boom in Mineral Markets: How Long Might It Last?” Resources Policy, vol. 33, no. 3, September 2008, pp. 125-128. Co-authored with M. Radetzki, G. Lagos, M. Lima, and J.E. Tilton.

“The Mineral Economies: Performance, Potential Problems, and Policy Challenges,” pp. 7-48 in Managing Mineral Wealth (Addis Ababa, UN Economic Commission for Africa, 2004). I also wrote the Introduction and edited the entire set of papers in this 200-page book, which represents a set of training materials (for students and government officials) on the management of mineral wealth and the role of mineral wealth in economic development.

“La Situacion de Estados Unidos,” pp. 90-137 in Acceso a mercados para minerales y metales en América (Gobierno de Chile, Ministerio de Minería y Comisión Chilena del Cobre, 2003). Co-authored with Luis Sosa and Claudio Valencia. [“The Situation in the United States,” pp. 90-137 in Market Access for Minerals and Metals in the Americas, Government of Chile, Ministry of Mines and Chilean Copper Commission, 2003.]

"Mineral and Metal Prices: Mechanisms, Instability, and Trends," in William A. Hustrulid and Richard L. Bullock, editors, Underground Mining Methods: Engineering Fundamentals and International Case Studies (Littleton, Colorado, SME, 2001). Co-authored with Peter A. Howie.

"Sustainable Development and the Mineral Industry," in James M. Otto and John Cordes, editors, Sustainable Development and the Future of Mineral Investment (Paris, United Nations Environment Programme, 2000).

"Managerial Risk Taking: A Study of Mining CEOs," Mining Engineering, March 1996, pp. 61-67. Co-authored with Michael R. Walls.

"Dzialalnosc gornicza oraz ochrona srodowiska: ekonomia, polityka panstwa oraz zarzadzanie," pp. 27-50 in I Szkola Gospodarki Surowcami Mineralnymi (Krakow, Polska Akademia Nauk, 1993). ["Mining, Mineral Processing, and the Environment: Economics, Public Policy, and Management"]

"Managing for Successful Mineral Exploration: A Review," Resources Policy, vol. 19, no. 3, pp. 173-176, 1993.

"Exploration," pp. 21-67 in Merton J. Peck, Hans H. Landsberg and John E. Tilton, editors, Competitiveness in Metals: The Impact of Public Policy (London, Mining Journal Books, 1992).

"The Status of Superconductors and Their Potential Impacts on the Mineral and Metal Industries," Materials and Society, vol. 15, no. 3, pp. 195-210, 1991. Co-authored with B. Yarar and J. Trefny.

"Cyclical Instability in Major Metal Markets: An Empirical and Conceptual Introduction," Resources Policy, vol. 17, no. 2, 1991, pp. 91-99.

"The Passenger Car Industry," pp. 161 - 215 in John E. Tilton, editor, World Metal Demand: Trends and Prospects (Washington, D.C.: Resources for the Future, 1990).

"Exploration and Access to Public Lands," Resources Policy, vol. 15, no. 2, 1989, pp. 115-130.

"Metal Demand: Secular Change and Long-Run Prospects," pp. 33-41 in John A. Cordes and Thomas Torries, editors, Surplus Capacity in the International Metals Industry (Littleton, Colorado: Society of Mining Engineers, 1989). Co-authored with John E. Tilton.

"Exploration in the United States," pp. 331-362 in John E. Tilton, Roderick G. Eggert, and Hans H. Landsberg, editors, World Mineral Exploration: Trends and Economic Issues (Washington, D.C.: Resources for the Future, 1988). Co-authored with Arthur W. Rose.

"Base and Precious Metals Exploration by Major Corporations," pp. 105-144 in John E. Tilton, Roderick G. Eggert, and Hans H. Landsberg, editors, World Mineral Exploration: Trends and Economic Issues (Washington, D.C.: Resources for the Future, 1988).

"Changing Patterns of Materials Use in the U.S. Automobile Industry," Materials and Society, vol. 10, no. 3, 1986, pp. 405-431.

"National Security and Recent Trends in U. S. Mining and Mineral Processing," Materials and Society, vol. 10, no. 2, 1986, pp. 113-129.

"A Simple Econometric Analysis of Metals Exploration Expenditures: The United States, Canada, and North American Firms", Modeling and Simulation, vol. 16, 1985, pp. 1381-1386.

"Exploration's Role in Iron and Aluminum Supply Since the Second World War," Natural Resources Forum, vol. 9, no. 3, 1985, pp. 187-196.

"Mineral Exploration in the USSR and the USA," Resources Policy, vol. 11, no. 2, 1985, pp. 128-140.

"Metamorphic equilibria in the siliceous dolomite system: 6 kb experimental data and geologic implications," Geochimica et Cosmochimica Acta, vol. 45, 1981, pp. 1039-1049. Co-authored with D. M. Kerrick.

Essays, Papers Aimed at a General Audience, and Special Issues of *Resources Policy*

"Energy-critical elements for sustainable development," MRS Bulletin, vo. 37, no. 4, April 2012, pp. 405-410. Co-authored with Alan J. Hurd, Ronald L. Kelley, and Min-Ha Lee.

"Minerals go critical," Nature Chemistry, vol. 3, September 2011, pp. 688-691.

"Critical Minerals and Emerging Technologies," Issues in Science and Technology, vol. XXVI, no. 4, Summer 2010, pp. 49-58.

"Trends in Mineral Economics: Editorial Retrospective, 1989-2006," Resources Policy, vol. 33, no.1, March 2008, pp. 1-3.

Mineral Investment Risk and Opportunities in Asia, special issue of Resources Policy, vol. 24, no. 2, June 1998. Editor.

National Mineral Policies in a Changing World, special issue of Resources Policy, vol. 23, no. 1/2, June 1997. Co-edited with James Otto.

Competitiveness and Sustainability in Natural Resource Exploitation, special issue of Resources Policy, vol. 22, no. 1/2, June 1996. Co-edited with Marian Radetzki.

"Sustainability and Resources Policy," Resources Policy, vol. 21, no. 1, 1995, pp. 3-4.

"Mineral Resources," Encyclopedia of the Future (New York, MacMillan, 1995).

"Critical Issues in the Reform of Mining Law in the United States," JOM, April 1995, pp. 44-45.

"Reforming the Rules for Mining on Federal Lands," Resources, Fall issue 1994, pp. 6-9.

"The Next Twenty Years," Resources Policy, vol. 20, no. 1, 1994, pp. 3-4.

Competitive Strength in Mineral Production, special issue of Resources Policy, vol. 18, no. 4, December 1992. Editor.

Living with Cyclical Instability, special issue of Resources Policy, vol. 17, no. 2, June 1991. Co-edited with David Humphreys.

Papers in Conference Proceedings

"Mining Taxation and Economic Rents: A U.S. (Economist's) Perspective," pp. 167-187 in Eugenio Figueroa, editor, Economic Rents and Environmental Management in Mining and Natural Resource Sectors (Santiago, Chile, University of Chile and University of Alberta, 1999).

"National Mineral Policies and the Location of Exploration," Presidential Address, pp. 1-8 in Proceedings of the Mineral Economics and Management Society (Houghton, Michigan, Mineral Economics and Management Society, 1997).

"The Role of Public Policy in Exploration," pp. 5-10 in Peter Crowley, editor, Asia Pacific Resource Development: Exploration and Mining Policy Directions (Canberra: Minerals and Energy Forum, 1994).

"Metal Recycling and Its Impact on the Demand for Metallic Ores: The Case of Copper," pp. 69-78 in C. Diaz and others, editors, Copper 91-Cobre 91: Plenary Addresses, Economics, and Applications of Copper (New York: Pergamon Press, 1991).

"Economists and Denver's Brown Cloud," pp. 219-224 in Sharon D. Sweet, editor, Proceedings of the Brown Cloud Forum (University of Denver Atmospheric Sciences Center, Technical paper 1988-1). Co-authored with R. H. Patrick.

Book Reviews

Review of Wyatt M. Rogers, Third Millennium Capitalism: Convergence of Economic, Energy, and Environmental Forces (New York, Quorum Books, 2000), in Choice, 2000.

Review of James T. Hamilton and W. Kip Viscusi, Calculating Risks: The Spatial and Political Dimensions of Hazardous Waste Policy (Cambridge, Mass., MIT Press, 1999), in Choice, vol. 37, no. 5, January 2000.

Review of Richard M. Auty and Raymond F. Mikesell, Sustainable Development in Mineral Economies (Oxford, Clarendon Press, 1998), in Choice, vol. 37, no. 3, November 1999.

Review of Gill Owen, Public Purpose or Private Benefit? The Politics of Energy Conservation (Manchester, Manchester University Press, 1999), in Choice, vol. 37, no. 3, November 1999.

Review of Emirates Center for Strategic Studies and Research, Gulf Energy and the World: Challenges and Threats, in Choice, vol. 36, no. 2, 1998.

Review of Richard D. Morgenstern, editor, Economic Analysis at EPA: Assessing Regulatory Impact in Choice (Washington, D.C., Resources for the Future, 1997), in Choice, vol. 35, no. 5, 1998.

Review of Timothy O’Riordan, editor, Ecotaxation (New York, St. Martin's Press, 1997), in Choice, vol. 34, no. 11/12, 1997.

Review of Peter H. May and Ronaldo Serôa da Motta, editors, Pricing the Planet: Economic Analysis for Sustainable Development in Choice, vol. 34, no. 6, February 1997.

Review of Earle A. Ripley, Robert E. Redmann, and Adele A Crowder, Environmental Effects of Mining in Environment, vol. 38, no. 9, 1996, p. 31.

Review of Kaulir Kisor Chatterjee, An Introduction to Mineral Economics in Economic Geology, vol. 89, no. 7, 1994, p. 1652.

Review of Institution of Mining and Metallurgy, Mining and the Environment 2: A Reference List, in Resources Policy, vol. 17, no. 2, 1991, p. 162.

Review of U. S. Bureau of Mines, Nonferrous Metal Prices in the United States Through 1988, in Resources Policy, vol. 16, no. 4, 1990, pp. 314-315.

Review of Daniel Sperling, ed., Alternative Transportation Fuels: An Environmental and Energy Solution, in Natural Resources and Environmental Administration, 1990.

Review of P. Arndt and G. W. Luttig, eds., Mineral Resources Extraction, Environmental Protection, and Land-Use Planning in Industrial and Developing Countries, in Natural Resources Forum, vol. 13, no. 2, 1989, pp. 172-173.

Review of Kenji Takeuchi and others, The World Copper Industry: Its Changing Structure and Future Prospects, in Natural Resources Forum, vol. 11, no. 4, 1987, pp. 393-394.

Review of John A. Wolfe, Mineral Resources: A World Review, in Resources, no. 81, summer/fall 1985, p. 9.

Working Papers

“The Availability of Indium: The Present, Medium Term and Long Term.” Under review for publication as a technical report of the National Renewable Energy Laboratory. Co-authored with Martin Lokanc and Michael Redlinger.

“The Availability of Tellurium: The Present, Medium Term and Long Term.” In preparation for publication as a technical report of the National Renewable Energy Laboratory. Co-authored with Martin Lokanc and Michael Redlinger.

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