



Assessment of Undiscovered Oil and Gas in the Arctic

Donald L. Gautier *et al.*
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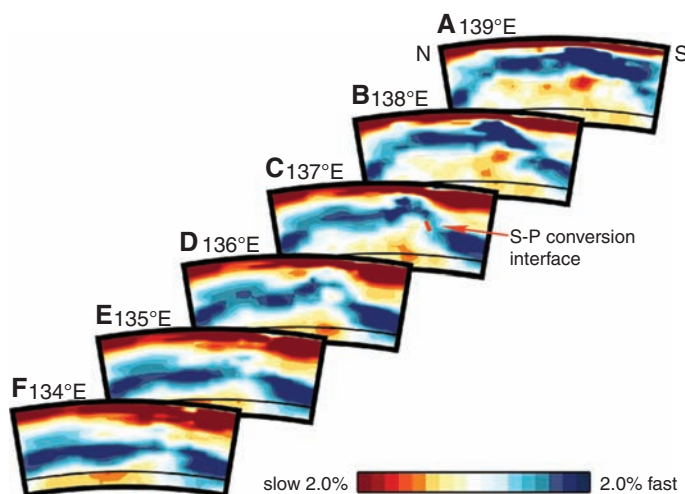
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Fig. 4. (A to F) Cross sections of the *P* wave speed anomalies along meridians from 134°E to 139°E at one-degree intervals. The depth range is from the surface to 800 km. A red line segment in (C) indicates the *S*-to-*P* conversion plane. The profiles for (A) and (F) are shown in Fig. 1B.



the shallower part. In the southern Mariana, differential slab dip between two adjacent segments has been detected and attributed to slab tear (24). We for the first time report the slab tear and consequent slab gap associated with slab stagnation.

The process of slab tearing should reflect the subduction history of the Pacific plate. Paleogeographic reconstruction models indicate that the Izu-Bonin trench migrated eastward with a clockwise rotation between the mid-Eocene and late Miocene, leading to the eastward migration of the junction of the Izu-Bonin and Japan trenches (25–27). This migration of the trench–trench junction implies an eastward migration of the tip of the slab gap, which should have been synchronous with the westward advance of the leading edge of the flattened part of the Izu-Bonin slab. Thus, the slab gap has extended over time both to the west and to the east.

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Figs. S1 to S8
References

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Assessment of Undiscovered Oil and Gas in the Arctic

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Among the greatest uncertainties in future energy supply and a subject of considerable environmental concern is the amount of oil and gas yet to be found in the Arctic. By using a probabilistic geology-based methodology, the United States Geological Survey has assessed the area north of the Arctic Circle and concluded that about 30% of the world’s undiscovered gas and 13% of the world’s undiscovered oil may be found there, mostly offshore under less than 500 meters of water. Undiscovered natural gas is three times more abundant than oil in the Arctic and is largely concentrated in Russia. Oil resources, although important to the interests of Arctic countries, are probably not sufficient to substantially shift the current geographic pattern of world oil production.

Among the greatest uncertainties concerning future energy supply is the volume of oil and gas remaining to be found in high northern latitudes. The potential for resource development is of increasing concern to the Arctic nations, to petroleum companies, and to all concerned about the region’s fragile environments.

These concerns have been heightened by the recent retreat of polar ice, which is changing ecosystems and improving the prospect of easier petroleum exploration and development. For better or worse, limited exploration opportunities elsewhere in the world combined with technological advances make the Arctic increasingly

attractive for development. To provide a perspective on the oil and gas resource potential of the region, the U.S. Geological Survey (USGS) completed a geologically based assessment of the Arctic, the Circum-Arctic Resource Appraisal (CARA), which exists entirely in the public domain.

Of the 6% of Earth’s surface encompassed by the Arctic Circle, one-third is above sea level and another third is in continental shelves beneath less than 500 m of water. The remainder consists of deep ocean basins historically covered by sea ice. Many onshore areas have already been explored; by 2007, more than 400 oil and gas fields, containing 40 billion barrels of oil (BBO), 1136 trillion cubic feet (TCF) of natural gas, and 8 billion barrels of natural gas liquids had been developed

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north of the Arctic Circle, mostly in the West Siberian Basin of Russia and on the North Slope of Alaska (1).

Deep oceanic basins have relatively low petroleum potential, but the Arctic continental shelves constitute one of the world's largest remaining prospective areas. Until now, remoteness and technical difficulty, coupled with abundant low-cost petroleum, have ensured that little exploration occurred offshore. Even where offshore wells have been drilled, in the Mackenzie Delta, the Barents Sea, the Sverdrup Basin, and offshore Alaska, most resulting discoveries remain undeveloped.

The CARA only considered accumulations with recoverable hydrocarbon volumes larger than 50 million barrels of oil or 300 billion cubic feet of gas (50 million barrels of oil equivalent, 50 MMBOE) (2). Smaller accumulations were excluded as were nonconventional resources such as coal bed methane, gas hydrates, oil shales, and heavy oil and tar sands. Geological risk was explicitly assessed, but technological and economic risks were not.

Resources were assumed to be recoverable even in the presence of sea ice or oceanic water depths. Initial results are presented without reference to costs of exploration and development.

Petroleum is overwhelmingly associated with sedimentary rocks. Therefore, a new map was assembled to delineate the Arctic sedimentary successions by age, thickness, and structural and tectonic setting (3). The map provided the basis for defining assessment units (AUs), which are mappable volumes of sedimentary rocks that share similar geological properties. The CARA defined 69 AUs (4), each containing more than 3 km of sedimentary strata, the probable minimum thickness necessary to bury petroleum source rocks sufficiently to generate significant petroleum. Areas outside the 69 AUs were interpreted to have low petroleum potential.

Geologic information about each AU was compiled from published literature and from data made available by cooperating organizations, including the Bundesanstalt für Geowissenschaften

und Rohstoffe, the Geological Survey of Canada, the Geological Survey of Denmark and Greenland, the Norwegian Petroleum Directorate, and the U.S. Minerals Management Service. Many active industry petroleum geologists also generously shared concepts and data. Although many organizations and individuals contributed to the geological analysis, the numerical assessments are the sole responsibility of the USGS.

The study relied on a probabilistic methodology of geological analysis and analog modeling (2). Burial history-fluid evolution models were prepared with use of standard modeling software such as PetroMod (<http://www.petromod.com/>) and BasinMod (www.platte.com/). On the basis of the presence and maturity of source rock, migration pathways, reservoir, and trap and seal, geologists postulated the presence of petroleum systems for review by the CARA team. Analogs were derived from a world database of 246 AUs previously defined for the USGS World Petroleum Assessment 2000 (5). The 246 AUs, which account for

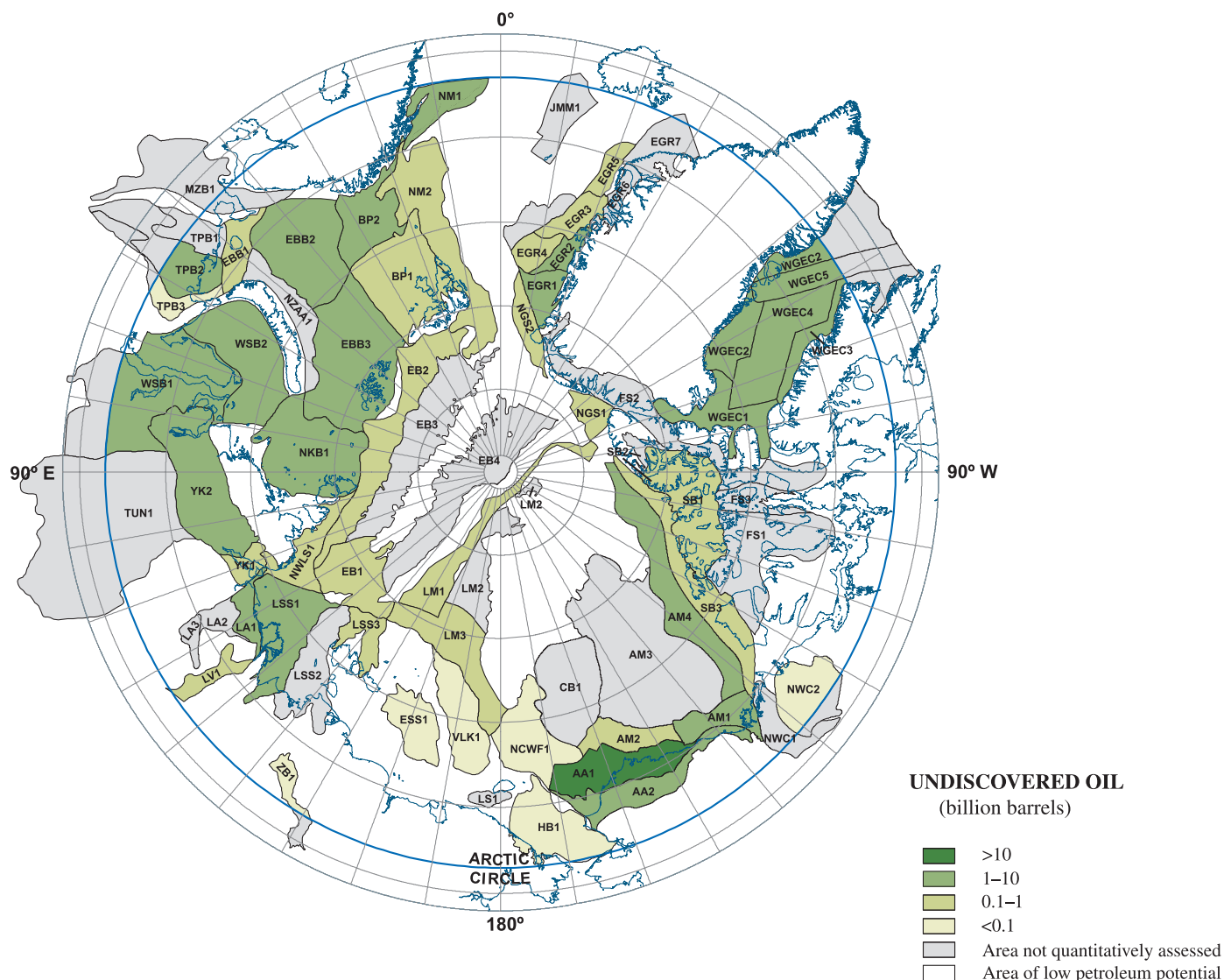


Fig. 1. Map showing the AUs of the CARA is color-coded for mean estimated undiscovered oil. Only areas north of the Arctic Circle are included in the estimates. AU labels are the same as in table S1. Black lines indicate AU boundaries.

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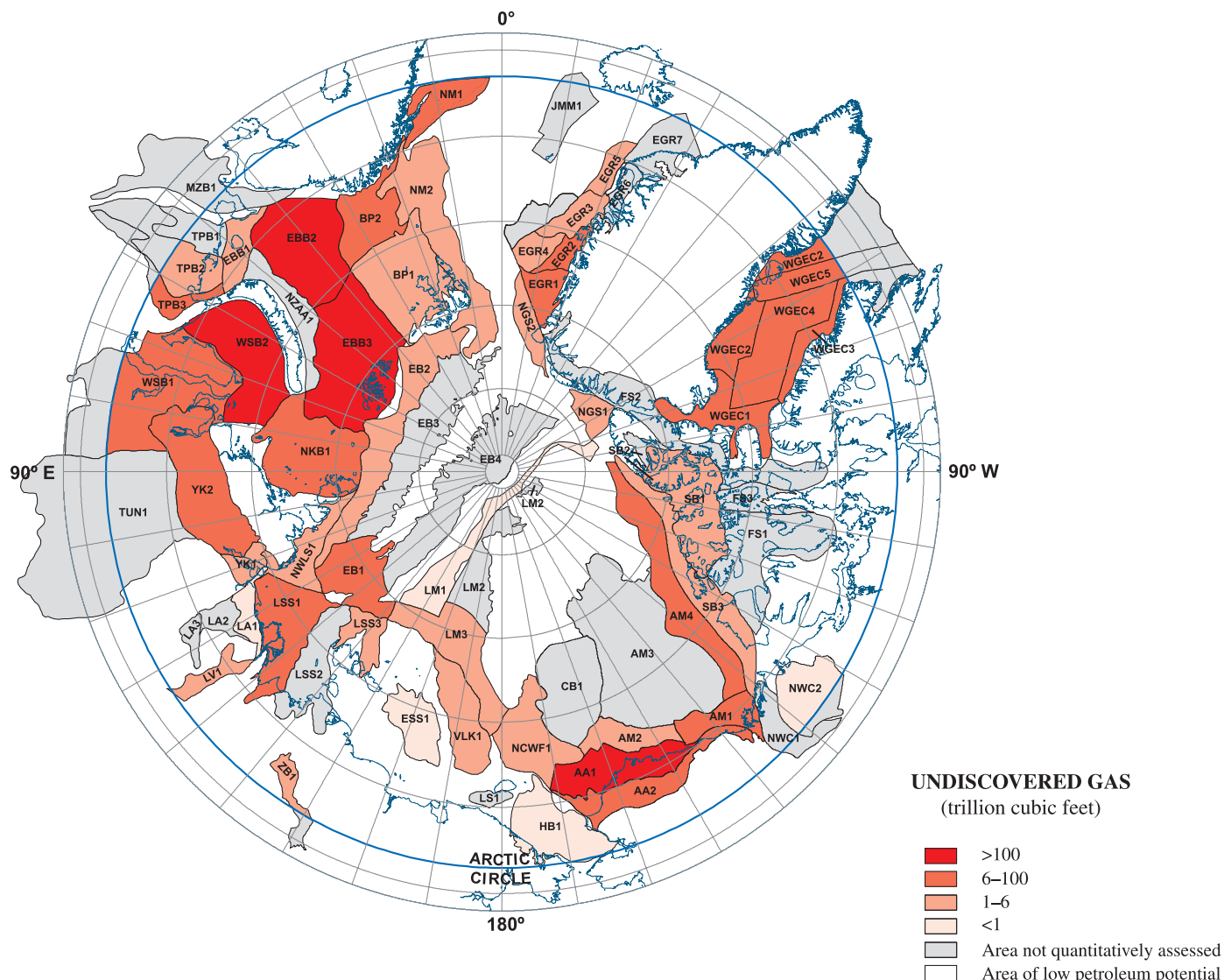


Fig. 2. Map showing the AUs of the CARA is color-coded for mean estimated undiscovered gas. Only areas north of the Arctic Circle are included in the estimates. AU labels are the same as in table S1. Black lines indicate AU boundaries.

more than 95% of known oil and gas outside the United States, were classified according to geologic parameters such as age of source rocks, structural style, and tectonic setting (6). With use of data from IHS Incorporated (1), we identified oil and gas fields in each of the 246 AUs and used them to compile global distributions for field sizes, field densities (fields per 1000 km²), and other parameters.

The CARA team analyzed each Arctic AU to determine the geologic properties most likely to control the sizes and numbers of undiscovered petroleum accumulations. Families of AUs from the analog database with similar geologic properties were identified. For example, the assessment units of northeastern Greenland exhibit the geologic features of rift-sag basins and rifted passive continental margins. Accordingly, for the assessment of northeastern Greenland, groups of analogs were selected from the world's population of rift-sag basins and rifted passive margins. In most

cases, field data from these populations of analogs provided numerical information for the assessment.

The marginal (unconditional) probability that at least one undiscovered accumulation greater than minimum size (>50 MMBOE) exists within the AU was assessed on the basis of three geologic elements: charge, including source rocks and thermal maturity; rocks, including reservoirs, traps, and seals; and timing, including the relative ages of migration and trap formation, as well as preservation.

The marginal probability of each AU was calibrated against a ranked list of all other CARA AUs. Only CARA AUs with known accumulations were assigned a probability of 1; AUs with <0.1 probability were not quantitatively assessed (table S1). Worldwide, 50 to 60% of similarly defined AUs contain at least one accumulation >50 MMBOE (7). However, the resulting mean of assessed AU probabilities in this study is about 41%, significantly less than the global average. This difference reflects the geo-

logic judgment of the CARA team that the petroleum potential of the Arctic differs somewhat from the global population of petroleum basins.

Given the presence of at least one accumulation, three conditional distributions were assessed for each AU: the numbers of undiscovered accumulations, the size frequency of undiscovered accumulations, and the likelihood of oil versus gas in each accumulation. The three conditional distributions were combined in a Monte Carlo simulation of 50,000 trials. Forty-nine of the 69 AUs were quantitatively assessed. Quantitative results of the CARA are listed in table S1 and illustrated in Figs. 1 and 2.

Individual AU assessments were statistically aggregated into Circum-Arctic totals, taking into account partial correlations between AUs with geologic similarities (2, 8). The CARA results suggest there is a high probability (>95% chance) that more than 44 BBO, a one in two chance (50%) that more than 83 BBO, and a 1 in 20 chance (5%) that as much as 157 BBO could be added to proved

reserves from new oil discoveries north of the Arctic Circle. Correlation increases the spread in estimated aggregate volume compared with an assumption of geologic independence. A perfect positive correlation, although geologically unreasonable, would yield the widest spread of aggregate volumes. If perfect positive correlation among all AUs were assumed, the estimated volume of undiscovered oil would range from about 22 BBO to about 256 BBO.

The mean estimate is more than double the amount of oil that has previously been found in the Arctic. For comparison, at the end of 2007, world proved reserves of oil, excluding Canadian oil

sands, stood at about 1238 BBO and consumption was about 30 BBO per year (9). On the basis of the USGS World Petroleum Assessment 2000 (5) adjusted for discoveries since 1996, the Arctic may contain about 13% of the mean estimated global undiscovered oil resource of about 618 BBO. Assuming reserves in existing fields will increase by an additional 400 BBO, undiscovered oil in the Arctic may account for almost 4% of the world's remaining conventionally recoverable oil resources.

All 49 assessed AUs were estimated to contain undiscovered oil, but 60% of the resource is concentrated in just six of them. The Alaska

Platform stands out (Fig. 3), with more than 31% of mean undiscovered Arctic oil (27.9 BBO). Other important AUs include the Canning-Mackenzie (6.4 BBO), North Barents Basin (5.3 BBO), Yenisey-Khatanga (5.3 BBO), Northwest Greenland Rifted Margin (4.9 BBO), and two AUs on the northeast Greenland Shelf: South Danmarkshavn Basin (4.4 BBO) and the North Danmarkshavn Salt Basin (3.3 BBO). The Alaska Platform is already a well-known petroleum-producing area; new discoveries there could maintain the flow of Alaskan oil for many years to come. Oil discoveries in the other areas could change the economic landscape and way of life of local inhabitants. However, the estimated resource is probably not sufficient to shift the world oil balance. Moreover, the estimated oil resources, if found, would not come into production at once but rather be added to reserves and produced incrementally.

On an energy-equivalent basis, we estimate that the Arctic contains more than three times as much undiscovered gas as oil. The estimated largest undiscovered gas accumulation is almost eight times the estimated size of the largest undiscovered oil accumulation (22.5 BBOE versus 2.9 BBO) and therefore more likely to be developed (table S1). The aggregated results suggest there is a high probability (>95% chance) that more than 770 TCF of gas occurs north of the Arctic Circle, a one in two chance (50%) that more than 1547 TCF may be found, and a 1 in 20 chance (5%) that as much as 2990 TCF could be added to proved reserves from new discoveries. For comparison, current world gas consumption is almost 110 TCF per year. The median estimate of undiscovered gas is a volume larger than the volume of total gas so far discovered in the Arctic and represents about 30% of global undiscovered conventional gas.

Two-thirds of the undiscovered gas is in just four AUs (Figs. 2 and 4): South Kara Sea (607 TCF), South Barents Basin (184 TCF), North Barents Basin (117 TCF), and the Alaska Platform (122 TCF). The South Kara Sea, the offshore part of the northern West Siberian Basin, contains almost 39% of the undiscovered gas and is the most prospective hydrocarbon province in the Arctic. Although substantial amounts of gas may be found in Alaska, Canada, and Greenland, the undiscovered gas resource is concentrated in Russian territory, and its development would reinforce the preeminent strategic resource position of that country.

It is important to note that these estimates do not include technological or economic risks, so a substantial fraction of the estimated undiscovered resources might never be produced. Development will depend on market conditions, technological innovation, and the sizes of undiscovered accumulations. Moreover, these first estimates are, in many cases, based on very scant geological information, and our understanding of Arctic resources will certainly change as more data become available.

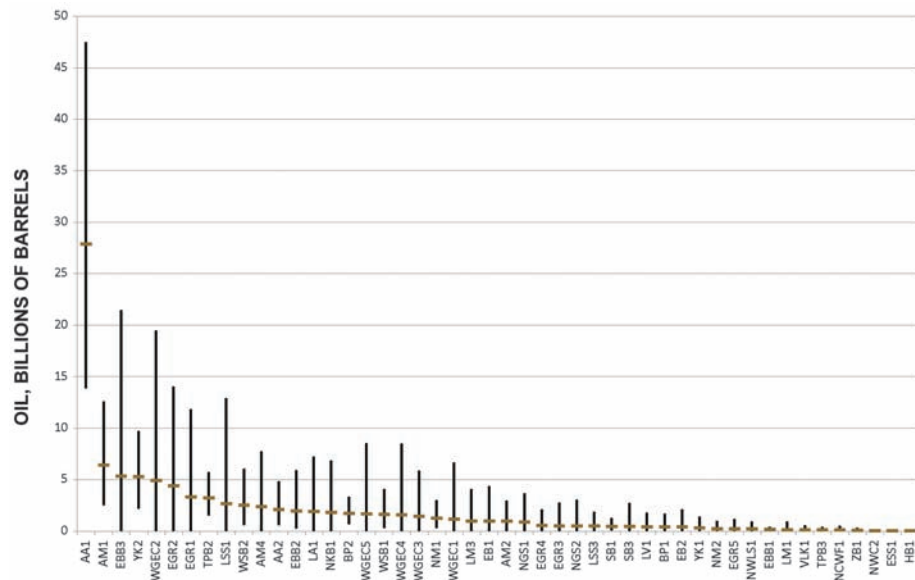


Fig. 3. Estimated undiscovered oil resources, in BBO, north of the Arctic Circle in AUs of the CARA. Vertical lines indicate the range of estimated oil resources from a 5% probability (fifth fractile) to a 95% probability (95th fractile). Horizontal lines correspond to mean estimated oil volumes.

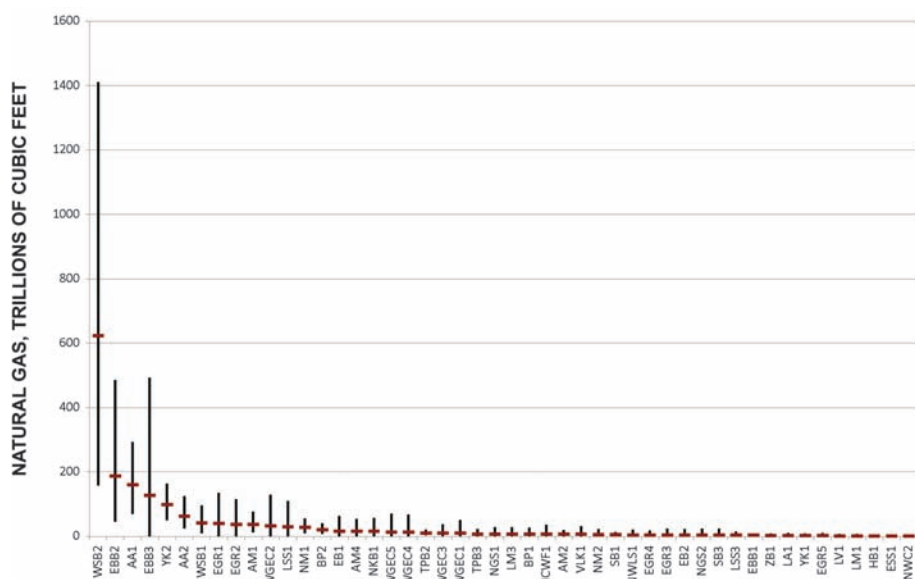


Fig. 4. Estimated undiscovered natural gas resources, in TCF, north of the Arctic Circle in AUs of the CARA. Vertical lines indicate the range of estimated natural gas resources from a 5% probability (fifth fractile) to a 95% probability (95th fractile). Horizontal lines correspond to mean estimated natural gas volumes.

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Supporting Online Material

www.sciencemag.org/cgi/content/full/324/5931/1175/DC1
Materials and Methods
Table S1

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Volcanism, Mass Extinction, and Carbon Isotope Fluctuations in the Middle Permian of China

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The 260-million-year-old Emeishan volcanic province of southwest China overlies and is interbedded with Middle Permian carbonates that contain a record of the Guadalupian mass extinction. Sections in the region thus provide an opportunity to directly monitor the relative timing of extinction and volcanism within the same locations. These show that the onset of volcanism was marked by both large phreatomagmatic eruptions and extinctions amongst fusulinacean foraminifers and calcareous algae. The temporal coincidence of these two phenomena supports the idea of a cause-and-effect relationship. The crisis predates the onset of a major negative carbon isotope excursion that points to subsequent severe disturbance of the ocean-atmosphere carbon cycle.

The temporal link between mass extinction events and large igneous province volcanism is one of the most intriguing relationships in Earth's history, with the end-Permian extinction–Siberian Traps association being the most celebrated (1, 2), but the causal link is far from resolved. A major problem is that the site of volcanism can rarely be directly correlated with the marine extinction record (3), and so comparison can only be achieved with the use of geochronological bio- and chemostratigraphic correlation techniques, with their inherent timing inaccuracies. To clarify some of these relations, we have studied the Emeishan flood basalt province in southwest China, where Middle Permian platform limestones pass up into a volcanic pile with interbedded limestones. These record both a marine extinction record and a major C isotope excursion. Thus, we were able to document multiple

phenomena associated with the Middle Permian mass extinction within the same geological sections.

Middle Permian (Guadalupian) platform carbonate rocks of the Maokou Formation are widespread throughout south China. In western Guizhou, southern Sichuan, and Yunnan Provinces they pass laterally into the flows of the Emeishan large igneous province (Fig. 1). The original size of the province is difficult to estimate because much has been eroded (scattered outcrops of contemporaneous volcanic rocks are found up to 300 km from the main sections, Fig. 1), but its main outcrops cover 2.5×10^5 km² in southwest China; the original volume was probably substantially less than 1×10^6 km³ (4). Despite their relatively small size, the coincidental timing of the Emeishan eruptions with the Guadalupian mass extinction has led to suggestions that they may be implicated in this environmental calamity (2, 5).

Sections from both within the volcanic province and around its margins record a prolonged phase of stable carbonate platform deposition before its termination by abrupt base-level changes. To the north of the province, in northern Sichuan, the Maokou limestones are capped by a karstic surface dated by conodont studies to

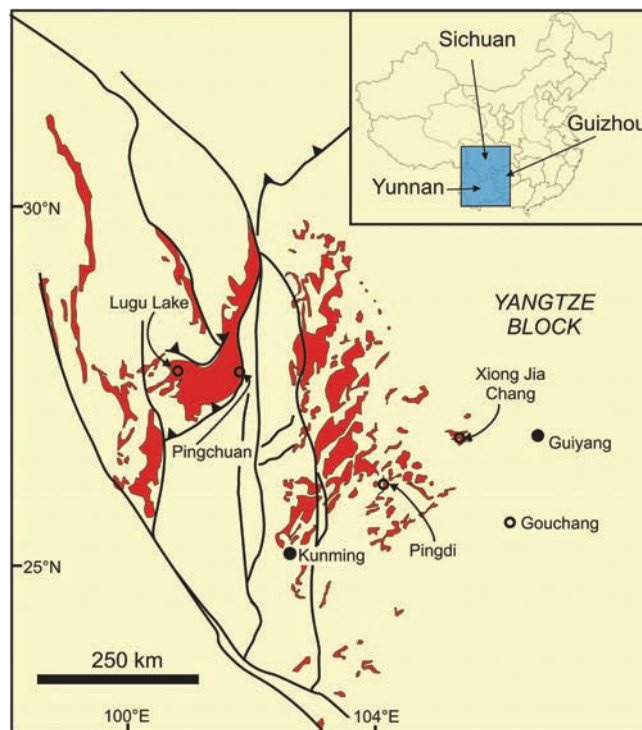


Fig. 1. Outcrop map (red) of the Emeishan large igneous province in southwest China (4).

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