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Crustal processes in Maine*

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Abstract

Greatly increased efforts in the mineralogical sciences, especially in metamorphic and igneous petrology as well as mineral physics, will be needed to support investigations, planned and underway, of the processes that form and modify the continental crust. These efforts will require large teams of earth scientists and will utilize methods such as superdeep drill holes, reflection and refraction profiles, long transects, and studies of deep xenolith suites. In order to justify the large costs of such projects, they must result in a significantly enhanced understanding of crustal processes. The increased knowledge about geologic relations at depth, which is the key to a more comprehensive understanding of crustal processes, is further refined when it is combined with improved methods in geochronology, geochemistry, and geothermobarometry.

Drawing upon participation in the Quebec–Maine–Gulf of Maine Global Geoscience Transect, in which a large amount of detailed data about geologic relations throughout the crust has been obtained from seismic reflection and refraction profiles combined with digitized geologic, gravity, and magnetic data, I offer several speculations. These speculations are about processes along the buried southeastern edge of the Middle Proterozoic Grenville province overridden by Taconian and Acadian thrusts, about Mesozoic crustal extension in Maine, and about the amount and sources of sediments in the Central Maine synclinorium.

Although the Grenvillian crust averages 40 km in thickness, the crust in Maine that includes the southeastern edge of the Grenville province is only about 40 to 42 km thick despite once having been buried by at least 25 and possibly as much as 35 km of Paleozoic thrust sheets. The present crustal thickness has resulted from several crustal processes that operated at different periods of time. Grenvillian crust was thinned by extension to about 20 km before it broke up in Late Proterozoic and Early Cambrian time to form an ocean basin. Loading of the remaining continental edge (Grenvillian crust with its slope-rise cover sequence) by Taconian thrust sheets formed overthickened crust that rose isostatically by thermal recovery and erosion during the Silurian and Early Devonian. Crustal thickening during the Acadian orogeny was concentrated along the thickest Taconian crustal section; in both orogenies this locus of overthickened crust lay above the rifted edge of the old Grenvillian crust. The Acadian thickening resulted in partial melting to yield garnet rhyolites in Maine and hinged isostatic rebound in New Hampshire due to thermal recovery.

The crust thins from about 41 km in western Maine to about 34 km in the Gulf of Maine. Despite earlier expectations, the crust varies little in thickness when passing beneath the inferred boundaries of the principal Paleozoic tectonostratigraphic terranes. The thinning actually takes place in steplike regions about 15 km wide where the Moho rises 3 or 4 km. The steplike regions lie beneath highly laminated crust that forms by ductile extension of deep crust beneath old faults that were extended in the shallow and middle crust to become listric at depth; overall crustal extension is 15 to 20%. Thus the Moho in the region was formed in the Mesozoic and does not significantly reflect Paleozoic accretionary processes. A wide range of igneous, metamorphic, and geophysical features can now be systematically related to extension, failure, and re-formation of the deep continental lithosphere during the early Mesozoic.

The volume of Silurian and Devonian metasedimentary rocks now present in the Central Maine synclinorium can be estimated from seismic reflection and refraction data to be approximately 870 km^3 per kilometer of length along strike. At least as much again is

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inferred to have been present in the Devonian from the pressures estimated from Acadian metamorphic assemblages in the region. Thus crustal thickness after the Acadian orogeny could have been 46 to as much as 51 km. The sources for such a huge volume of sediment could not have been just to the north and west. A possible source to the south and east could be rocks like those now found beneath the southeastern border of the synclinorium; these rocks were metamorphosed at midcrustal depths in the Middle Ordovician, and they could have been the temporal equivalent to the Taconian orogen along the northwest boundary of the Central Maine synclinorium.

Introduction

The earth sciences community has a large and ever increasing interest in the processes that form and re-form the continents. Greatly increased efforts in the mineralogical sciences, especially in metamorphic and igneous petrology as well as mineral physics, will be needed to support rapidly growing programs of deep continental studies. One of my activities as President of the Mineralogical Society of America has been to try to make it easier for MSA to participate more fully in the reporting of the results of such studies by meetings with the American Geophysical Union as well as the Geological Society of America.

The emphasis on continent-forming processes is the result of widespread review and appraisal of research opportunities in the earth sciences by numerous national and international peer groups. The very high priority being given deep continental studies is apparent from the commitments being made to large programs in seismic reflection profiling, deep and superdeep drilling programs, numerous studies along long international transects in the International Lithosphere Program, and increased attention to studies of deep xenolith suites. Many millions to many tens of millions of dollars per year are being spent by countries like the USSR, West Germany, Canada, and the United States to understand more about the processes that operate deep in the Earth's crust. One of the basic reasons for such high levels of funding is that something over 97% of Earth's history is stored in rocks older than approximately 180 m.y., and such rocks are found only in the continents. Commonly, research on deep crustal projects requires the efforts of teams of scientists for years and involves expensive data acquisition efforts—these projects are what are called "big science." Past President Ribbe has had his reservations (Ribbe, 1988) about the possible impact of the funding allocations for "big science" projects on reducing the funding available for the more usual one- or two-person research project. Thus if "big science" projects are to be justified, they must result in much new understanding of the processes that operate to form and modify the crust.

I will use some of the results of a "big science" crustal transect (Fig. 1) across southern Quebec, Maine, and the Gulf of Maine to oceanic crust south of Georges Bank by a team of United States and Canadian earth scientists with many different specialties. I am a participant in these studies. Our team synthesizes geologic and geophysical data for the Earth's surface and seismic reflection and refraction data for the deep crust into detailed descriptions of crustal blocks; we also make interpretations of the processes that have formed, modified, and even re-formed the deeper parts of the crust of Maine and adjacent areas. Our work is not yet finished, and thus I will emphasize some speculations of my own. But first, I must introduce you to the regional setting (Fig. 1).

Maine is entirely within the Appalachian orogen that was formed in various episodes during the Paleozoic. Although we could spend the day discussing the various extant versions of how this all happened, the basic facts follow. The orogen formed along the Late Proterozoic to Early Cambrian rifted margin of the Laurentian craton within Middle Proterozoic crystalline rocks of the Grenville province. A considerable, if uncertain, number of tectonostratigraphic terranes that differ principally in the nature of their Middle to Late Proterozoic, Cambrian, and Ordovician history, stratigraphy, and paleontology make up the orogen; in general these terranes accreted to the continent at successively younger times toward the southeast, although some had been joined together as composite terranes before accretion to the craton (Boone and Boudette, 1989, for example). Apparently, several modes of accretion were followed: ocean closing with obduction and subduction, collision of a microcontinental plate or two with Laurentia, major strike-slip faulting subparallel to the continental edge, and subsequent oblique obduction of yet another continental block. Although there are more details than can be dealt with here, it is appropriate to note that the Appalachians reflect accretion to Laurentia of predominantly continental blocks rather than growth through the separation of magma from the mantle, either directly or as extracts from subducting plates, as summarized for the western North American Cordillera by Ernst (1988). It should be interesting to compare the effects of crustal extension on the continental masses that result from these two different styles of continental accretion.

It will be no surprise that I believe that there is still a lot to be learned from the Appalachians. This mountain belt is young enough to include deformed fossiliferous supracrustal rocks and to have preserved sufficient traces of its history in its minerals and rocks so that this history can be deciphered to yield an understanding of the processes that have formed and re-formed it. More complete knowledge and interpretation of its faunal and mineral assemblages will be needed, of course. The processes that

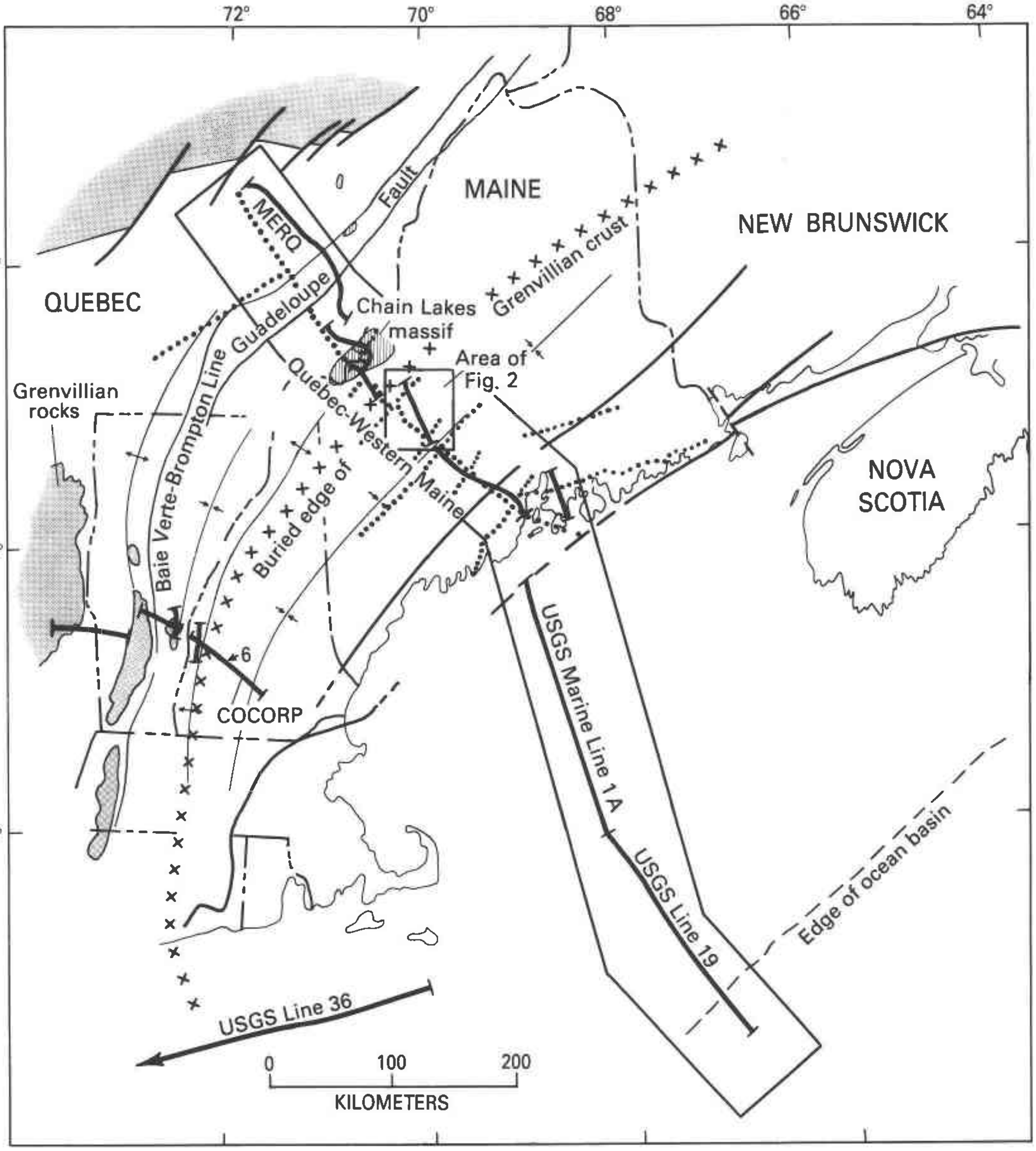

Fig. 1. The Quebec–Maine–Gulf of Maine transect is 100 km wide and 880 km long and crosses the northern Appalachians approximately normal to regional strike from the Laurentian craton (outcropping Middle Proterozoic Grenvillian granulites shown by shading) to the ocean basin (oceanic crust). The southeastern edge of Grenvillian crust at depth is shown by the line of crosses as inferred from seismic reflection data (Spencer et al., 1989; Phinney and Roy-Chowdhury, 1989). The Proterozoic Chain Lakes massif is shown by the ruled pattern. Some of the seismic reflection profiles in the region are shown by heavy lines, and seismic refraction data by lines of dots. The rectangle shows the location of the area in Figure 2 and the location of the cross section in Figure 3.

formed the Appalachians terminated long ago, and the evidence for them may be preserved only in the brittle upper part of the crust. Data obtained in projects that study the deep continental crust, such as the one in which I have participated, would be more readily interpretable if the processes studied were still active. Understanding of the data we have accumulated requires close comparison with data from much younger, still active, orogenic zones, which I will allude to in my speculations.

Let me immodestly suggest that the portion of the Appalachians north of the Hudson River will be the region where many of the new concepts about the origin of the whole range will be won. This is because the fresh outcrops in the northern Appalachians are favorable for geologic mapping, and these good maps have in turn led to numerous recent studies of metamorphic petrology, isotopic geochemistry, and geochronology. The fossil record in the internal parts of the orogen is more extensive in the northern Appalachians. There also are very extensive recent investigations of the crust of the region by Canadian and U.S. scientists on land and especially at sea by seismic reflection and refraction techniques, extensive application of time-temperature-pressure modeling of metamorphism and plutonism, interesting (and perplexing to me) notions of the role of large volumes of fluid in metamorphism, and so forth. All of these different kinds of studies, and others as well, contribute significantly toward more comprehensive understanding of the third dimension, depth. *Increased knowledge about geologic relations at depth is absolutely vital for progress to be made.* Such knowledge is increasingly obtainable, although the acquisition of some of it incurs the large costs associated with "big science" projects. Substantial sums have been committed for deep seismic studies of the northern Appalachians over nearly a decade, and much has been learned as we shall see.

Zartman (1988) discussed the evolution of thinking about the structural blocks of New England that has resulted from three decades of advances in geochronology. He correctly pointed out that the primary purpose of most recent studies has been the identification of terranes and the determination of the structural relationships of their boundaries. Possibly because he was writing a refereed paper, he stopped short of predicting the future. Not so constrained, I emphatically assert that the next decade of northern Appalachian studies will be dominated by revelations about the third dimension of the structural blocks of the region and that these revelations, especially when taken together with increased knowledge of the timing of events, will lead us to new concepts of the processes involved. Of course, petrologic, isotopic, and geochemical data for magmas that sampled their source regions deep in the crust and mantle (such as Ayuso, 1986; Ayuso et al., 1988; Beivier, 1988) and studies of xenolithic samples brought up from these regions will make important contributions. Greater knowledge of the third dimension will be derived by integration of the results from the new generation of geophysical data—e.g., seismic reflection and refraction results combined with derivatives of gravity and magnetic data—such as we are doing with the Quebec–Maine–Gulf of Maine transect, our colleagues working offshore are doing, and our Canadian colleagues are doing with Lithoprobe East. We will also benefit from increasingly sophisticated and geophysically constrained modeling of time-temperature-pressure paths of metamorphism and plutonism within the component blocks of the orogen.

The Quebec-Maine-Gulf of Maine transect

I have been involved with many colleagues at the USGS, the Geological Survey of Canada, State and Provincial geological surveys, and several universities since 1982 in gathering and interpreting data for a second-generation continent-ocean transect across the Appalachian orogen. This transect starts on the Grenvillian crust near Quebec City, Quebec, and crosses the entire orogen to end on oceanic crust (Fig. 1). This transect was designed to acquire much more complete information about the third dimension of the crust than was possible for the first-generation continent-ocean transects from the Decade of North American Geology (DNAG) program that are now being published by the Geological Society of America as part of its centennial. Each of these DNAG transects is a swath 100 km wide and many times longer in which the description of the crust to Moho depths was attempted without the opportunity to acquire new geophysical data.

For our second-generation transect, several million dollars worth of deep seismic reflection profiles on land and sea, specifically sited to support the transect, was acquired. In addition, seismic refraction profiles parallel and normal to regional structural grain were shot on land and at sea. Gravity and magnetic data were also acquired during the seismic field programs, and these results and those by others were added to large, carefully revised and new regional gravity and magnetic compilations. Improvements in processing and displaying each of these constituent data sets are constantly being made. In addition, special emphasis has been given to digitizing all of these data, as well as the geologic maps, so that data can readily be exchanged among a network of computers where they are processed into new combinations. The digitized data also will be used to produce color separates for printing and will be archived on optical discs in a CD-ROM format readily accessible to PC-level microcomputers. Participating in each of these tasks at one level or another has been a remarkably interesting and occasionally exciting educational process for me, particularly when a new bird species for my life list appeared during winter field work or at sea! I'll have to forego discussion of the data formats, digital line-graph coding, gridding intervals, three-dimensional modeling software, and other geographic information systems technology we have had to develop (Stewart et al., 1987), although I am certain that this technology will be essential for future progress in crustal studies.

After nearly two years of efforts to assemble the required data sets, we are able to prepare fairly detailed digital three-dimensional crustal models and a whole spectrum of new images of crustal features. In Figure 2 the simplified digitized geology is shown from the new bedrock geologic map of Maine (Osberg et al., 1985) for a region 50 by 65 km in size centered on the Lexington batholith in west-central Maine. Features of interest are that the plutons seem to be blob- or drop-shaped bodies emplaced within the metasedimentary cover sequence of the region, that Middle Proterozoic Grenvillian crust is inferred to lie below crust containing the Proterozoic Chain Lakes massif, and that the crust thins to the southeast as shown by the rise of the Moho. I will return to the last two items in detail below. Contours of the shape of the composite granitic Devonian Lexington batholith are shown at the center of Figure 2. The shape of the Lexington batholith shown here and on the cross section (Fig. 3) was modeled by my colleague J. D. Phillips as

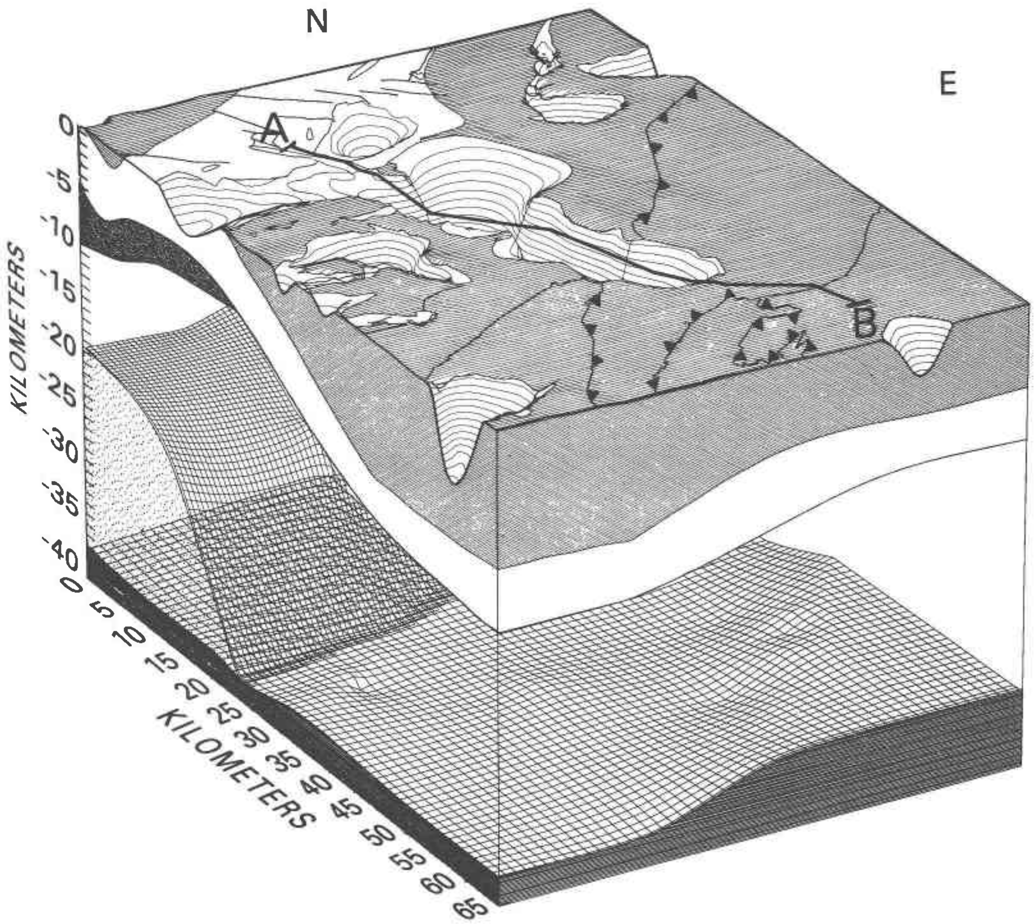

Fig. 2. Three-dimensional model of the crust created from digital data sets for an area 50 by 65 km in size centered upon the Lexington batholith in west-central Maine. Vertical and horizontal scales are identical. The geologic map of the surface was generalized from Osberg et al. (1985). Faults are shown by lines; a thrust fault is shown by teeth on the upper plate. The shapes of the plutons deduced from modeling gravity and magnetic data are shown as cavities with contours at 0.5-km intervals. The metasedimentary rocks of the Central Maine synclinorium are shown by a ruled pattern; Cambrian and Ordovician rocks are unpatterned. The remaining deeper crust is mostly continental in composition. The base of the crust, or Moho, as inferred from seismic refraction and reflection data, is shown by a grid pattern overlying mantle shown by heavier ruled lines. The crust thins by about 3 km over an interval of about 15 km in the lower right of the model. This is one of two such "steps" on the Moho observed in Maine along the transect. The southeastern edge of the Grenvillian crust is shown at the bottom and back of the model (dot pattern). It has been overridden by northwest-directed thrusts that carry the Chain Lakes massif (dark pattern) at about 5- to 10-km depth. The surfaces bounding the rock masses of this model have all been digitized so that a geologic cross section through the model can be drawn quickly in any direction. The cross section along the line A–B is shown in Figure 3.

the best fit for gravity and magnetic data collected during the seismic field work (Phillips et al., 1988), using density and magnetic susceptibility measurements on specimens collected along the profiles. All the plutons intrude the Silurian and Devonian metasedimentary rocks of the Central Maine synclinorium. These metasedimentary rocks unconformably overlie Cambrian and Ordovician ophiolite and mélange that lie upon the buried Proterozoic Chain Lakes massif that crops out just north of the test area (Fig. 1). The thickness and southeastern extent at depth of the Ordovician and older rocks are still speculative, with only one of several alternative models shown.

This reasonably detailed three-dimensional model for the region was constructed by use of many combinations of digitized geologic and geophysical data. Computer programs enable cross sections to be drawn rapidly in any direction. The cross section in Figure 3 is drawn along the seismic reflection profile we ran almost north-south across the middle of the region (Unger et al., 1985; Stewart et al., 1986). A migrated line drawing of reflections seen on the seismic reflection profile is also shown in this cross section. In addition to these reflections, the three-dimensional model also is supported by a number of seismic refraction lines and by numerous images made up by

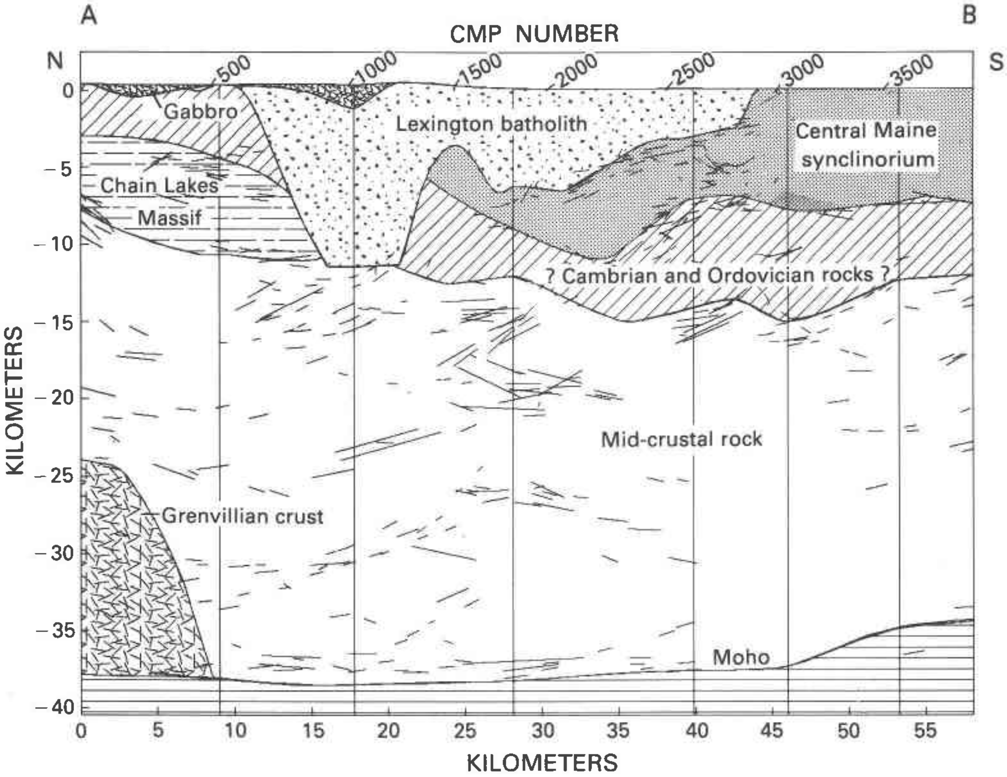

Fig. 3. Cross section A–B through the model of the crust shown in Figure 2. Reflectors are shown in a seismic reflection profile along line A–B after migration with the velocity function $V = 5.7 + 0.05z$, where V is in kilometers per second and z = depth in kilometers. The shape of the Lexington batholith was modeled by using measured densities for field samples to fit the gravity data measured along the seismic reflection profile. There is excellent agreement between the independent seismic reflection and gravity data sets on the shape of the batholith; reflectors are absent in the batholith. Numerous midcrustal reflectors must still be interpreted.

combinations of the digitized geologic map and band-pass–filtered gravity or magnetic data. These new kinds of images, made possible by using new computer technology, reveal many details about the upper part of the crust, especially when shown in color as on the cover of the April 1988 issue of *Geotimes.* Folds in magnetic pyrrhotite-bearing country rock, previously unknown mafic dikes, the shapes and compositions of the plutons, and other details can be seen and can be confirmed with independent seismic reflection and refraction data. Reprocessing of the seismic reflection data for the upper 15 km of the crust and display of the amplitude of the reflectors in color (J. D. Unger and C. Spencer, oral communication, 1988) show that the base of the Lexington batholith is not sharp against the country rock; there is a zone about 2 km thick where energy is weakly reflected, a finding not expected for homogeneous plutonic rock. This zone is either highly injected country rock, or more likely, in my opinion, contains many blocks stoped from the roof of the pluton. Combining the shape from the seismic profile with the mapped outline of the pluton by use of a proprietary software program, we obtained a model of the shape of the batholith and can compute its volume. Soon we plan to develop software programs to iteratively best-fit the modeled shapes of bodies with observed and calculated gravity and magnetic data.

A comparison of the combined geologic map with the derived geophysical data and a map of the isograds in the area by Holdaway et al. (1986) shows that the isograds around the southeastern part of the Lexington batholith are far from the batholith and are not underlain by granitic rock. This finding indicates that the source of heat for these metamorphic reactions was from above and that the gentle upward and outward funnel-shaped flaring of the pluton suggested by our model continued upward for at least several kilometers. The metamorphic high east of the central part of the Lexington batholith appears to be above a mafic pluton buried deeper than the depths of the folded magnetic metapelite imaged by the shallow magnetic data, say more than about 4 km. Holdaway (personal communication, 1987) has found float blocks of mafic rocks that may have originated from dikes in this area.

Similar images for the central Maine coast also yield a wealth of information about the upper third of the crust, and many details can be confirmed by the independent seismic reflection and refraction data. The Lucerne pluton Wones (1980) discussed can be seen to flare upward from a source located along the older Turtle Head fault zone. The granitic batholith beneath Acadia National Park can be shown to be underlain as well as surrounded by gabbro. Given so much information on the shapes and compositions of plutons in the region, even where they occur under the sea, and our control from seismic refraction and reflection data, we should be able to make good estimates of the relative proportions of mafic and felsic plutons in the coastal region and thus constrain models of magma genesis. The westerly dip of the magnetic basement of the coastal antiform as it passes beneath the Central Maine synclinorium is apparent, as it also was in the seismic reflection profile (Unger et al., 1987). There is much detail about the correct locations of important regional faults in Penobscot Bay, which are quite different from the positions shown on the state bedrock map. Major revisions of the cross sections shown for the coastal antiform on the 1985 Maine map are required.

It is plain that the procedures just outlined will be sufficient basis for a credible geologic map for the large part of our transect that lies beneath the Gulf of Maine and for which "ground truth" in the form of rock samples is quite limited. However, to date, only a small fraction of the anticipated flood of combined geologic-geophysical images has been produced, and three-dimensional models that use all of our data are few.

Now I would like to speculate on what our transect might tell us about some processes that formed the crust of Maine. First, I will speculate about the buried southeastern edge of the Grenville province that was overridden by a thick stack of Taconian allochthons and later was overridden by Acadian allochthons. The overridden Grenvillian crust should have been deeply depressed into the mantle, yet no overthickened crust is observed now. Where has it gone, and when did this happen? Second, I shall attempt a preliminary overview of the effects of Mesozoic crustal extension across our transect. I think some ideas can be tested, and the basic concept may be valuable in understanding the eastern margin of the orogen. After all, there is an Atlantic Ocean out there, and a macrocontinent did stretch and break up to form the type "Atlantic passive margin." Then I will discuss our new estimates about the volume of Silurian and Early Devonian protoliths in the Central Maine synclinorium and the implications that these estimates have for modeling Acadian metamorphism and plutonism. Finally, I will try to articulate the regional structural problem posed by the need to find sources for such a large volume of sediment in a comparatively brief interval of geologic time.

Some processes along the edge of Laurentia buried by the Taconian and Acadian orogenies

Zen (1983) deduced the position of the southeastern edge of the Laurentian continent from a thoughtful, even prophetic, analysis of geologic data when only a minimum amount of seismic reflection data was available. Subsequently, the buried edge of the continent has been repeatedly recognized in seismic reflection images, and speculations about processes along the buried edge are in vogue (Keen et al., 1986; Phinney, 1986; Hutchinson et al., 1986; Spencer et al., 1989; Marillier et al., 1989; Phinney and Roy-Chowdhury, 1989). The location of the inferred buried edge of Laurentia is shown in Figure 1 and lies approximately along the tectonic hinge line shown in Figure 4, which is not coincidental in my view.

Seismic reflection and refraction data from the northwestern part of our transect (Spencer et al., 1989) indicate that at depth the Grenvillian rocks of the Laurentian continent extend for nearly 200 km southeastward from Grenvillian outcrops to almost 40 km southeast of the Quebec-Maine border. These data show that Grenvillian rocks at their southeastern edge were thinned from their original thickness (of about 42 km) to less than half this amount during crustal extension that culminated with continental breakup and formation of an ocean basin in latest Proterozoic to earliest Cambrian time (Williams and Hiscott, 1987). Petrographic studies of xenolith suites from dikes that cut rocks southeast of the Guadeloupe fault (Fig. 1) by Trzcienski and Marchildon (1989) support our seismic interpretation, as Grenvillian lithologies and kyanite-bearing metapelite that may have been derived from Cambrian slope-rise sediments on Grenvillian basement were found.

During the late Middle Ordovician Taconian orogeny, a stack of northwest-directed thrust sheets amounting to at least 25 km in thickness were obducted onto Laurentia in the region of the Chain Lakes massif (Fig. 4), just south of the international boundary, and an entirely different kind of Proterozoic crust was thrust over Grenvillian crust (Boone and Boudette, 1989). By analogy to younger mountain belts such as the Northern Rockies and Himalayas, such a great thickness of allochthonous sheets should have formed a very thick crust, at least 50 and possibly 60 km thick. However, overthickened crust is not found in the region today.

Indirect evidence suggests that an overthickened crust once existed along the southeastern edge of the old craton after the Taconian orogeny. There undoubtedly were rocks, now eroded, that covered the Chain Lakes massif where the crust is now approximately 40 km thick. Doherty and Lyons (1980) estimated that the present surface was at a depth of 5–7 km in the Jurassic. It is difficult to estimate how thick the cover sequence might have been in the Silurian and Devonian. Estimates of the depth of emplacement of the Devonian plutons that intrude the massif, based on metamorphic mineral assemblages in their contact aureoles (Biederman, 1984) and on models of cooling history (Heizler et al., 1988), range from 7.6 to 12 km. Crust as thick as 50 km, and possibly several kilometers more, seems possible in the Late Ordovician after the Taconian orogeny.

Stratigraphic evidence from adjacent synclinoria indicates that the inferred overthickened crust along the suture at the edge of the old craton was being heated and was buoyantly rising during the Silurian and Early De-

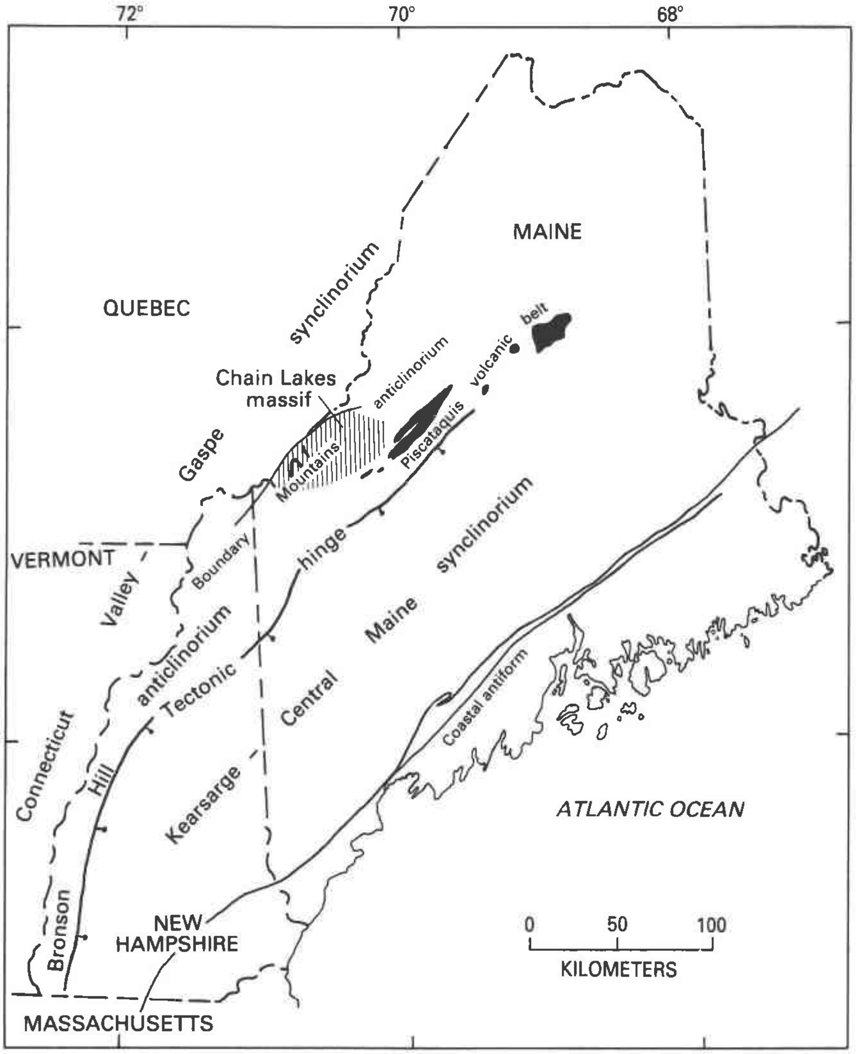

Fig. 4. Map showing the location of principal geologic features discussed in the text. The buried southeastern edge of Laurentia is located approximately below the tectonic hinge line found in Silurian metasedimentary rocks by Hatch et al. (1983) and Moench and Pankiwskyj (1988).

vonian. Regionally, crust having the greatest thickness of obducted thrust sheets makes up the 60-km-wide Boundary Mountains anticlinorium (Fig. 4). This anticlinorium extends to the northeast and southwest of our transect for about 120 km and possibly for as much as 1000 km to the northeast (Boone and Boudette, 1989) beneath younger rocks. It is flanked to the northwest and southeast by synclinoria that were filled with Silurian and Lower Devonian sediments. Regional mapping summarized by Moench (1984) and Moench and Pankiwskyj (1988) reveals that the Chain Lakes massif was unroofed in the Silurian and that its distinctive diamictite clasts were being shed into nearby conglomerates. These coarse sedimentary rocks contrast with the predominant wacke, shale, and minor carbonate sedimentary rocks farther away in adjacent synclinal basins.

Our seismic reflection profile (Spencer et al., 1989) crosses a narrow belt of Devonian metasedimentary rocks bounded by steep northwest-dipping faults. The fault on the southeast side of these Devonian rocks places them against the Chain Lakes massif and is a normal fault (Westerman, 1983, p. 92), along which the "core of the Boundary Mountain anticlinorium was rising relative to the basin to the northwest"; and the direction of movement from slickensides is south side almost directly up dip, suggesting that the crust beneath the massif continued to rise isostatically for as much as several kilometers through Lower Devonian sediments because of thermal recovery of its thick root during Devonian or later time. Alternatively, the belt of Devonian metasedimentary rocks between the Boundary Mountains fault and formations to the northwest could be an east-directed Acadian thrust fault like those described by Cawood and Williams (1988). If so, the sequence of processes would be emplacement of Taconian allochthons, Silurian and Devonian sedimentation along with thermal recovery of the suture or root zone, followed by Acadian compression and eastward thrusting.

The Moose River synclinal belt of Lower Devonian shallow-water clastic rocks with volcanic detritus (Boucot, 1961) and the slightly younger superimposed belt of felsic volcanic centers called the Piscataquis volcanic belt (Fig. 4) by Rankin (1968) lie immediately east of the southeastern edge of the Grenvillian craton that we have located at depth and extend northeasterly for 160 km across north-central Maine. Some of the rhyolitic volcanic centers in the Piscataquis belt erupted distinctive garnet rhyolites (Rankin, 1968, 1980). The garnet composition is 80 to 90% almandine with most of the remainder being pyrope. Such garnet rhyolites originate only by fractional melting of felsic rocks at lower-crustal or upper-mantle pressures of 15 kbar or more, equivalent to >50-km depth (Green and Ringwood, 1968; Fitton, 1972; Wood, 1974). Such a deep source corroborates the postulated overthickening along the buried suture over the edge of the Laurentian continent, but leaves open the question of whether the thick crust resulted from Taconian or Acadian compression. Although Rankin interpreted the garnet rhyolites as an oceanic volcanic arc, our group has found no evidence for high seismic velocities indicative of ocean crust in Maine (Luetgert et al., 1987), nor is there Pb-isotope evidence in plutonic feldspars for a major component of oceanic crust in the region (Ayuso et al., 1988).

The differences in kinds and amounts of Silurian metasedimentary rocks have been used by Hatch et al. (1983) and Moench and Pankiwskyj (1988) to define a tectonic hinge zone that extends southwesterly into New Hampshire for hundreds of kilometers (Fig. 4). In central New Hampshire, Ando et al. (1984) and Phinney and Roy-Chowdhury (1989) have interpreted Grenvillian crust to extend eastward at depth to about the hinge line. Overlying the postulated Grenvillian crust is the gneiss dome terrane called the Bronson Hill anticlinorium, which has been interpreted by these workers to have been transported northwestward to its present location along intracrustal detachments. Silurian and Devonian rocks rest unconformably upon the Late Ordovician volcanic rocks of this anticlinorium, which in turn were unconformably deposited upon older gneisses that make up the layered cores of the domes (Schumacher, 1988; G. W. Leo, in preparation). All these rocks are complexly folded and were metamorphosed to kyanite grade at 15-km or greater depths in the Acadian orogeny. Rise of the cores of the gneiss domes of the anticlinorium postdated most of the Acadian folding. Gneiss domes are unusual in New England, and I can't help but speculate that these deep-seated domes and their kyanite-bearing country rocks are exposed as a result of unusual geologic circumstances. I suggest that while northwesterly transport was important, a vital component was the buoyant rise of overthickened crust as it recovered thermally. The crust in the region was first overthickened by being overridden during the Taconian orogeny, and then it was overthickened again by compression during the Acadian orogeny. Chamberlain and England (1985, p. 600–601) suggested that the kyanite-bearing assemblages in the Bronson Hill anticlinorium resulted from the more rapid Devonian erosion of the Bronson Hill region in contrast to the Kearsarge–Central Maine synclinorium immediately to the east where the same formations contain sillimanite-bearing assemblages. Tracy and Robinson (1980) deduced from prograde reaction textures that the Bronson Hill rocks were subjected to peak metamorphic pressures earlier than the peak processes in the Kearsarge–Central Maine synclinorium. These observations are consistent with my suggestion of buoyant rise of overthickened crust, augmented by westward and upward thrusting along the imbricate structures imaged by seismic reflection profiles in the region (Ando et al., 1984; Phinney and Roy-Chowdhury, 1989). Harrison and Spear (1988) and Harrison et al. (1989) have proposed rapid uplift of 5 km or more based on the pattern of $^{40}Ar/^{39}Ar$ mineral ages across the Bronson Hill region.

The wide swath of buried Grenvillian crust southeast of surface exposures of such rocks seems not to have been destroyed by the various orogenies that formed the Appalachians, but to have been the basement for crust that was overthickened with stratigraphic, metamorphic, volcanic, and plutonic consequences. There can be no doubt that improved knowledge of the third dimension forces us to rethink our concepts of crustal processes along the orogen.

Mesozoic extension in Maine and the Gulf of Maine

After accretion of numerous tectonostratigraphic terranes to the North American continent was completed late in Paleozoic time, an enormous continent, Pangea—comprising much of North America, Africa, and western Europe—had been created. Sutures containing numerous kinds of faults with strikes more or less parallel to the long axis of the Appalachian orogen had been formed. In the Triassic, Pangea was subjected to intracratonal extension, for which direct evidence exists in the form of faulted basins or half-grabens. Many of the Paleozoic faults were reactivated to form the border faults for an extensive belt of basins and intervening ridges hundreds of kilometers wide that is elongated subparallel to Paleozoic structures. Many of these basins accumulated sedimentary sections 3 to 5 km or more thick, and so the throw on their border faults was at least that much and was even more where the basin sedimentary rocks were rotated to steep dips. The border faults commonly offset the latest metamorphic isograds of the country rocks and thus are younger. The faults have the characteristics of brittle fractures with thin mylonite zones and mineralized breccia fillings. There are many postmetamorphic north-

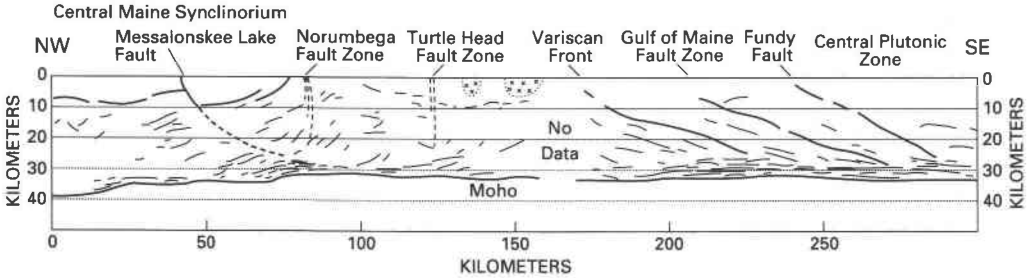

Fig. 5. Sketch of composite seismic reflection profile from the Central Maine synclinorium to the northwestern Gulf of Maine, after Unger et al. (1987) and Hutchinson et al. (1988). The Moho passes smoothly beneath major named faults that have been proposed as boundaries between tectonostratigraphic terranes. The Moho rises about 3 km in the region where a listric fault that breaks the basement and metasedimentary rocks of the Central Maine synclinorium merges into highly laminated deep crust. Principal Paleozoic thrust faults in the Gulf of Maine have reversed motion under extension and terminate against highly laminated crust above the Moho. These relations are caused by re-formation of the Moho during Mesozoic extension that increased toward the southeast.

east-trending faults in New England that show chracteristic brittle fracture, but as no contemporaneous Mesozoic sedimentary rocks are found and basins, if once present, have been eroded, the age of these faults usually is uncertain. In a few instances, breccias in the faults yield suggestions of Jurassic disturbance of $^{40}Ar/^{39}Ar$ ages (West et al., 1988).

Little has been known until recently about what becomes of the Mesozoic faults at depth. Cross sections have been drawn showing large blocks dropped deeply into the crust, but whether the border faults become listric, and if so, where, could not be resolved. The consequences for crustal thickness also were not resolved. Structural models indicate that crustal extension at least as much as the throw on the border faults would be necessary if the border faults became listric. We needed to know more about the middle and bottom of the crust.

Thousands of Triassic and Jurassic as well as younger Cretaceous dikes of various mafic compositions were emplaced in regional stress regimes so that they have similar preferred orientations throughout New England and the adjacent northern Appalachians (McHone, 1978, 1984). The regionally most common strike is northeast, but the farther north and east within the region or the younger in the Mesozoic, the more northeasterly the average strike. The dikes indicate extension of the crust normal to their strike. A genetic relationship between dike emplacement and the Jurassic opening of the North Atlantic ocean in the Early Jurassic is well established (McHone and Butler, 1984).

Two prominent steep gradients in the regional Bouguer gravity field of Maine (Kane and Bromery, 1968) are approximately parallel to regional structural grain. Until recently it was not known when these gradients were established (though commonly it was assumed to be during the Paleozoic orogenies) or whether they originated from crusts having different average densities (oceanic or continental compositions), different thicknesses, or greatly different thicknesses of younger cover sequences. Crustal thickness in Maine and New England was known only in broad outlines from older seismic refraction surveys and studies of seismic arrival times (Taylor and Toksoz, 1979).

Greatly improved knowledge of the variation of crustal thickness in the northern Appalachians has resulted from the large investments in seismic reflection and refraction surveys on land and sea and from reinterpretation of extensive seismic reflection profiling at sea done for oil and gas exploration (Ando et al., 1984; Hutchinson et al., 1986; Phinney, 1986; Keen et al., 1986; Hutchinson et al., 1988; W. Doll and J. K. Costain, personal communication, 1988). It is now known that the crust of the northern Appalachians is at most about 42 km thick beneath the western side of the orogen and is relatively uniform in thickness with only local undulations of a few kilometers as it thins gradually toward the southeast. On the southeast side of the orogen, the crust is about 35 km thick for hundreds of kilometers before it rapidly thins east of a tectonic hinge zone associated with the opening of the Atlantic Ocean. The continental edge had been thinned to about 20 km when it broke up (Schlee and Klitgord, 1988).

Luetgert (1985) has shown that the crust throughout Maine has nearly the same average velocity structure in all of the different tectonostratigraphic terranes and is of sialic bulk composition. No evidence has been found for measurable tracts having the high seismic velocities typical of transitional or oceanic crust. The reflection and refraction Moho under our transect in Maine are at virtually identical depths and show the same details. The crust thins from a thickness of 41 ± 1 km in the northwest near the Quebec-Maine border to 34 ± 1 km in the Gulf of Maine (Luetgert et al., 1987; Hutchinson et al., 1987; Unger et al., 1987). The thinning takes place in two steplike regions, each about 15 km wide, where the Moho rises 3 or 4 km (Fig. 5). Overall, the crust thins about 15 to 20%. The steps strike parallel to regional structures at the surface and are parallel to the previously identified gravity gradients, but they do not coincide with the gravity gradients spatially, being offset to the southeast by 5–15 km.

Crustal thickness, or depth to the Moho, remains nearly the same between the steps and for hundreds of kilometers on either side of the pair of steps. The depth to the Moho remains unchanged even when passing beneath several major faults thought to be the boundaries between the principal different Paleozoic tectonostratigraphic terranes (Unger et al., 1987; Hutchinson et al. 1988). *Thus the Moho in the region seems not to reflect Paleozoic crustal processes and is actually significantly younger, having been formed in the Mesozoic.* Similar results were found for the Appalachians south of Long Island (Hutchinson et al., 1986; Phinney, 1986; Phinney and Roy-Chowdhury, 1989) and elsewhere in the southern Appalachians (for example, Nelson et al., 1985). That the Moho is young and re-forms during crustal extension is a major discovery made through seismic reflection and refraction studies of the crust (Brown et al., 1986; Bois et al., 1988; Matthews and Cheadle, 1986).

Seismic evidence for the re-formation of the deepest parts of the crust during Mesozoic extension is well preserved along our transect. Extension that reverses the throw on inclined Paleozoic thrust faults is common in the Gulf of Maine. The footwall faults of some of the basins in the northwestern Gulf of Maine terminate against subhorizontal reflections near the Moho (Hutchinson et al., 1988). Upper Triassic and Lower Jurassic sedimentary rocks are found in many half-graben basins, and the throw and extent of the basins increase toward the southeast (Hutchinson et al., 1988). As the amount of extension increased toward the southeast, failure by pure shear with much associated extrusion of basalt and continental breakup occurred in Early Jurassic time. Offshore seismic reflection profiles show that the subsequent opening of the Atlantic was accompanied by thermal subsidence of previously extended crust, erosion of the upturned edges of rotated fault blocks, and, with thermal decay, transgressive deposition of sediment of the coastal plain across the broken remnants of the upper crust. This is evidence for a crustal process over a grand scale indeed!

The basement of the Central Maine synclinorium is offset about 4 km by an east-side-down normal fault that appears listric into laminated crust over the southeastern step where the Moho rises (Fig. 6). A prominent fault continues upward from the basement fault, breaking the Silurian and Devonian metasedimentary rocks of the synclinorium and reaching the surface on or near the trace of the Messalonskee Lake fault of Osberg (1988) and parallel to the trace of the Central Maine gravity gradient (Kane and Bromery, 1968). Osberg regarded this fault as an early Acadian thrust fault refolded in a later Acadian episode of folding. The orientation of this fault is favorable for its Mesozoic reactivation as a normal fault with east-side-down movement, and I suggest that field evidence for this hypothesis be sought.

Jurassic dikes and plutons are found in Maine and New Brunswick along the trace of the Central Maine gravity gradient (Larrabee and Spencer, 1963; Larrabee, 1963; Burke et al., 1973; Osberg et al., 1985). The coincident parallelism of the Central Maine gravity gradient, Jurassic intrusions, and a fault that breaks the cover sequence and becomes listric in the deep crust—all normal to the direction of largest crustal extension—are best explained by Mesozoic extensional tectonics.

Taken together, we have remarkably numerous details about the process of Triassic and Jurassic crustal extension along our transect. Close comparison in scale and duration can be made with the processes now causing continental rifting in the Basin and Range province of the western United States (McCarthy and Thompson, 1988; Allmendinger et al., 1987) or, in more advanced stages, the Red Sea (Girdler and Southren, 1987; Martinez and Cochran, 1988). Theoretical models developed for rifting (Buck et al., 1988; Bell et al., 1988; Dunbar and Sawyer, 1988; Crespi, 1988) predict most aspects of what we have observed. The principal process responsible for the crustal thickness and laminations near the base of the crust in Maine today was southeastward crustal extension along a deep crustal simple shear. As the lower crust was uniformly extended and locally was necked, the upper crust failed by brittle fracture. If weak zones, such as older faults, were present, they were preferred locations for failure along faults that became listric to the deep shear zone. The faulted blocks rotated toward the listric fault and were raised when concurrent necking of the deep crust occurred. Some smaller secondary fault blocks with antithetic displacements probably developed, but the overall polarity of the sense of rotation is in the direction of principal extension toward the southeast in the southern two-thirds of our transect (Hutchinson and Klitgord, 1988). The thinning of continental crust in New England occurred progressively from north to south, while concurrently migrating easterly into Maine and the Gulf of Maine.

The amount and effects of crustal extension are not sufficiently recognized in regions like Maine where early Mesozoic basins are absent. Not only is there vertical motion on the border faults of basins, but rotation of the block can occur, and the basement rocks of the footwall block can be concurrently uplifted. The systematic occurrence of younger formations on the northwest side of large blocks such as Nova Scotia and the coastal volcanic belt of Maine probably results from northwesterly rotation of these blocks during extension; the uplifted footwall edges of these large blocks were sources for the sediments in Triassic and Jurassic basins. I suggest that the conspicuously "notched" or "sawtooth" map pattern of isograds on the Maine map may originate from the erosional planing of a systematic array of southeast-side-down normal motions of fault blocks and rotations along older faults reactivated in the Triassic and Early Jurassic. The exposure of Carboniferous kyanite-grade (and hence midcrustal) rocks in southwestern Maine (Thomson and Guidotti, 1986) may be an example. This hypothesis may have applications in southeastern New England, such as

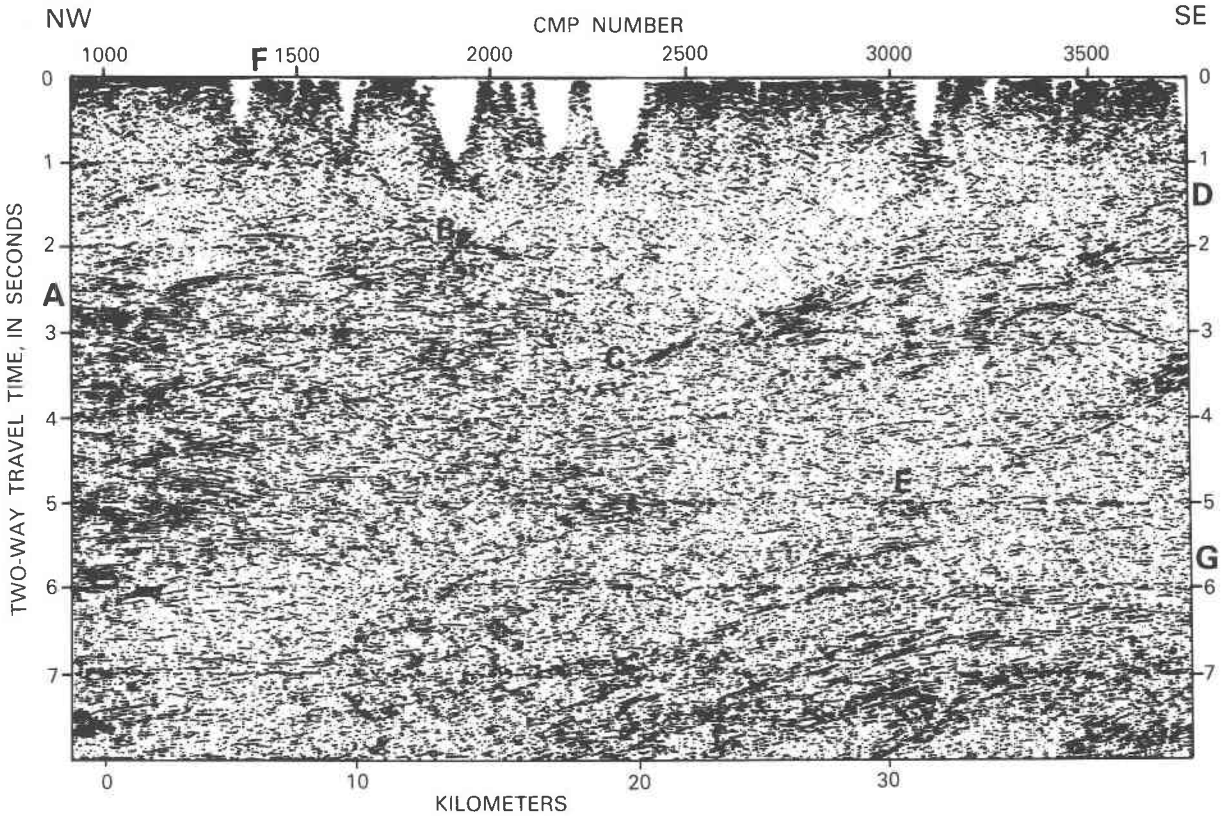

Fig. 6. Seismic reflection profile of part of the Central Maine synclinorium showing the basement of the synclinorium (A–B and C–D) and an east-side-down fault (F–B–C) that breaks the Silurian and Devonian rocks of the synclinorium in the interval F–B and becomes listric at depth (C–E–G). The deepest crust shown contains many laminated reflectors beneath which the Moho rises 1 s (~3 km) (not shown, see Fig. 5). These unmigrated data are from the U.S. Geological Survey–Geological Survey of Canada Quebec-Maine profile and were processed by Carl Spencer and colleagues at the Geological Survey of Canada. Depth in kilometers is approximately 3 times two-way travel time in seconds; horizontal and vertical scales are approximately equal.

to the high-grade rocks on the west side of the Beaverhead fault in Narragansett Bay. If Mesozoic displacements and rotations are concentrated in the fault zones along the boundaries between tectonostratigraphic terranes and are not recognized, they could significantly confuse and frustrate attempts to reconstruct the processes of terrane accretion.

The concept of re-formation of the deepest parts of the crust by plastic deformation and recrystallization has the corollary that deep granulite assemblages could be re-equilibrated and isotopic clocks could be reset. Thus the possibility of deep crustal rocks appearing to be as young as, or younger than, the rocks in the upper crust far above them is very real. Matte and Hirn (1988, p. 151) have reported just such an example from the deepest crust affected by Permian orogeny in France.

The recrystallization of the deep crust eliminates weaknesses along old faults and sutures so that after cooling, the deep crust becomes strong and rigid. The deep crust serves as a foundation that supports the weak and brittle upper crust; Koteff and Larsen (1989) have reported that during postglacial uplift of western New England, the crust rebounded without warping or discernible steps although old faults were numerous in the large region studied.

Understanding the third dimension, depth, especially in combination with a knowledge of timing, permits a new, more dynamic view to be used to replace the former concept of a nearly inert crust beneath the "passive" continental margin. A wide range of plutonic, metamorphic, and geophysical features now can be systematically related to extension and failure of the continental lithosphere.

Sedimentation in the Central Maine Synclinorium

By use of information from seismic reflection and refraction profiles, it is possible to calculate volumes of geologic features, such as magmatic intrusions, or other geologic phenomena, such as the sediments in a synclinorium. As a specific example, I shall discuss the implications of the very large volume of sediments in the Central Maine synclinorium.

The volume of the Central Maine synclinorium in the

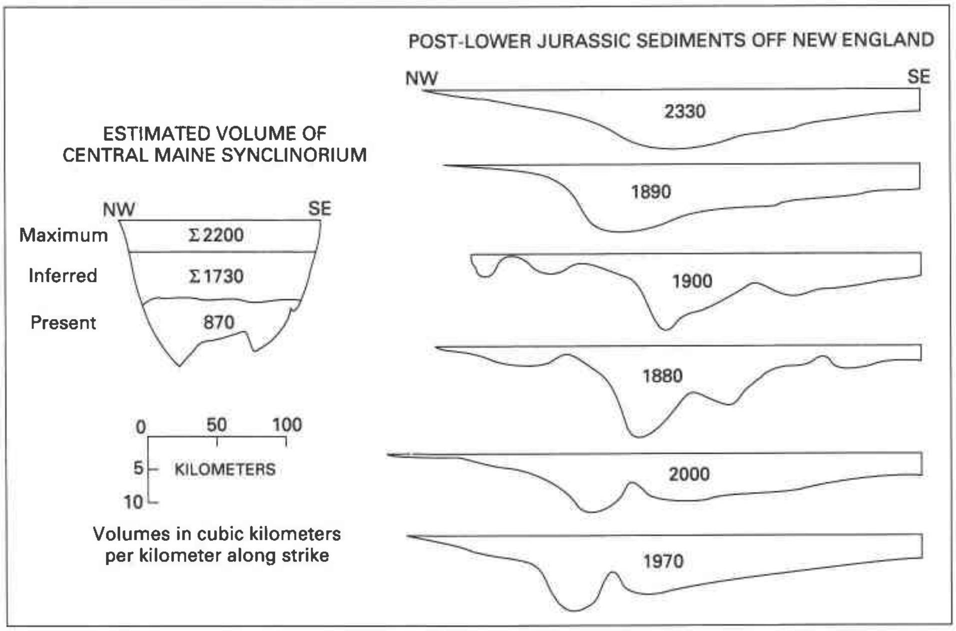

Fig. 7. Volume of metasedimentary rocks observed and inferred to be present in the Central Maine synclinorium per kilometer along strike compared to the volume of sediments in post–Lower Jurassic slope-rise sediments in the Atlantic Ocean for the region from central Long Island to central Nova Scotia (Tucholke et al., 1982). The sources that supplied such a huge volume of sediments to the Central Maine synclinorium in a relatively short time are problematic. A thick crust was formed when these sediments were compressed during the Acadian orogeny.

region of our transect consists of two parts, the volume now present and the volume that has been eroded (Fig. 7). The volume now present can be estimated from our seismic reflection profile, which is nearly normal to the axis of the synclinorium (Unger et al., 1987). Seismic velocity in the lower-grade metasedimentary rocks of the synclinorium is slower (Leutgert and Bottcher, 1987, and oral communications, 1988) than in the kyanite-grade basement rocks, dated as older by Olszewski and Gaudette (1988). The resulting velocity contrast makes the contact between the basement rocks and the rocks in the synclinorium a strong reflector over most of the seismic reflection profile. The depth of the synclinorium across the strike ranges from 10 to 5.5 km in the central two-thirds of the seismic reflection profile and averages about 8.3 km. Because the synclinorium averages 105 km in width, as shown on the geologic map of Maine (Osberg et al., 1985), the volume of metasedimentary rocks present today is approximately 870 km^3 per kilometer of strike length, ignoring the volumes of younger intrusions.

The volume of rock removed by erosion can be crudely estimated from consideration of the pressures calculated for Acadian metamorphic assemblages in the general region (Holdaway et al., 1982; Holdaway et al., 1988; Ferry, 1980). The lowest pressure estimate of Holdaway et al. (1988) is 2.35 kbar, equivalent to an additional 8.2 km of thickness and 860 km^3/km in volume, for a total of 1730 km^3/km along the strike of the synclinorium. Pressure increased during successive phases of Acadian metamorphism and also increased along the synclinorium toward the southwest. Holdaway et al. (1982) suggested an average pressure of 3.3 ± 0.4 kbar corresponding to depths of 10–13 km, and Ferry (1980) found the average pressure to be 3.5 ± 0.3 kbar (13 km).

Even the lowest pressure estimate yields a geologically large volume of synclinorial sediments: it is nearly equivalent to the average volume per kilometer of length along strike for all of the sediments that accumulated in the marginal basins of the western Atlantic Ocean off New England since the ocean opened. The volume of marginal basin sediments was approximated by measuring the areas in six cross sections, about 200 km apart, of the thickness of post–Lower Jurassic slope-rise sediments shown on the map of Tucholke et al. (1982) for the region from central Long Island to central Nova Scotia. Regions of eastern Nova Scotia strongly affected by sediments deposited by the St. Lawrence River were avoided, and the cross sections were stopped when abyssal-plain sediments were reached. Remarkably, the huge volume of sediments in the Central Maine synclinorium was deposited in only about 65 m.y., from about the end of the Middle Ordovician (constrained by the metamorphic age of the basement on the southeast border of the synclinorium) (Olszewski and Gaudette, 1988) to the time these rocks began to be folded and metamorphosed by the Acadian orogeny (Siegenian Age of the Early Devonian, Chamberlain and England, 1985; Osberg, 1988). If subsequent episodes of metamorphism at higher pressures are considered to have resulted from further sedimentation or volcanism, the thickness of the rocks in the synclinorium would have to be increased by as much as 5 km, and a corresponding increase would occur in the implied volume along strike to over 2200 km^3/km. However, such an increase is unlikely because sedimentation would be unlikely to continue during folding (Holdaway et al., 1982). The generally overweight appearance of the synclinorium now results from compressional shortening.

What use are such estimates? An obvious use is to constain estimates of overall crustal thickness at the end of Acadian metamorphism in the region of the synclinorium. The lowest estimate for Maine would the thickness of present crust (38 km) plus the inferred thickness of lowest Acadian metamorphic pressures (8 km), for a total of at least 46 km, not considering the effects of subsequent events such as Mesozoic extension. Crust as thick as 51 km is possible if higher regional metamorphic pressures are taken. Such speculations are obviously useful as constraints for thermal modeling of the genesis of Devonian and Carboniferous granites in the region. The seismic refraction data along strike for over 100 km northeast and southwest of the center of our transect in central Maine suggest that the volume of sediments in the synclinorium remains approximately the same along strike. As the amount of Acadian compression increased to the southwest and the synclinorium was narrowed to half the width it has in Maine, the very great thicknesses (~30 km) of multiply thrusted and folded rocks postulated for Massachusetts are to be expected. Either erosion was very rapid there, or the crust became very thick indeed in the Acadian orogeny. Peter Robinson may not be putting us on with his colorful cross sections drawn up in the air!

Our transect contains the area studied so thoroughly by Ferry (1980, 1986, 1987, 1988) to make his estimates of fluid flux in metamorphism. Ferry's estimates are for the amount of fluid that is out of chemical equilibrium with, and therefore reacting with, the rock it infiltrates. The volumetric fluid–rock ratio calculated by Ferry (1987, 1988) differs with metamorphic grade attained (higher grade has seen higher ratios), with rock composition (higher ratios in metapelites than in metacarbonates), and from bed to bed within the same lithology (different permeabilities). If the average regional fluid/rock ratio for the higher-grade rocks was as high as 1.4 (Ferry, 1988) or even 2.0 (Ferry, 1986), the amount of fluid that would be required for most of the contents of the synclinorium to attain high grade, as occurs along strike to the southwest in western Maine and central New Hampshire, is quite large. Ferry (1986) discussed the origin of so much fluid, which would have to occur in much greater amounts than would be available from dewatering of the synclinoral sediments. Lateral flow and recirculation are required, and so is heat. Now that the volume of the synclinorium has been estimated, modelers can use thermal history deduced from metamorphic blocking temperatures to determine if the internally generated and conductive heat supply was sufficient, or if heat supplied by magma introduced into the synclinorium from below is required. A more comprehensive hydrologic model may also be devised.

Another application of the volume calculations is to constrain the source of the sediments, which is to say the disposition of land masses at the time of sedimentation. Osberg (1978, 1988) has argued that the principal source of the sediments that filled the synclinorium was to the west. The limited capabilities of source regions to the west have been pointed out by Moench and Pankiwskyj (1988, p. 1–6). Only the tracts now occupied by the Boundary Mountains anticlinorium and the Bronson Hill anticlinorium could have been available as sources, and even parts of these later were covered by thin sediments. The Connecticut Valley–Gaspe synclinorium to the west of these tracts was concurrently receiving sediments and could not have been a source. Given the average width of the anticlinoria of about 60 km and neglecting any contribution from these tracts to the Connecticut Valley–Gaspe synclinorium, erosion of the anticlinoria of more than 28 km would have been required. Even the added volume possibly made available by the thermal recovery of the Taconian suture zone seems inadequate to supply such a large amount of sediment. The Silurian and Devonian rocks of the cover sequence of the Avalonian composite tectonostratigraphic terrane to the southeast of the Central Maine synclinorium also have been proposed as a source of sediments by Moench and Pankiwskyj (1988). Avalonia contains only shallow-water sediments and volcanics contemporaneous with the synclinorium, and these rocks have been metamorphosed only to lowest-greenschist facies and thus appear not to have been deeply eroded. It is even possible that this terrane had not yet been accreted. I believe a more likely source was rocks like those now found in the basement below the synclinorium. These rocks were metamorphosed to kyanite grade in the Middle Ordovician (Olszewski and Gaudette, 1988; Brookins and Hussey, 1978), which implies their burial to midcrustal depths of 15–17 km at that time. As they had been exposed at the surface by erosion when covered by the sediments of the synclinorium, rapid postmetamorphic uplift and erosion are implied. The existence of a substantial orogen along the southeastern flank of the synclinorium is implied by the tract of high-grade metamorphic rocks exposed in the coastal antiform. This orogen could well have been the temporal equivalent to the Taconian orogen on the northwest side of the microcontinental plate that underlies the Central Maine synclinorium. That it may have had substantial length along the axis of the northern Appalachians is implied by the appearance of comparable rocks and structures in southeastern New Hampshire, Massachusetts, and Maine (Olszewski, 1980; Olszewski and Gaudette, 1988), New Brunswick (Fyffe et al., 1988), Cape Breton Island (S. M. Barr and R. P. Raeside, written communication), and southern and eastern Newfoundland (Chorlton and Dallmeyer, 1986; Miller, 1988). It is, of course, possible that the source tract on the southeastern side of the Central Maine synclinorium was displaced by strike-slip faults subsequent to yielding sediments to the synclinorium.

Summary

New developments in geophysical data processing, combined with seismic reflection and refraction profiling and digitized maps, are affording very detailed information about the structure of the upper part of the crust and the processes that occurred there. Reasonably good resolution (<2 km) can be obtained for features as deep as the base of the crust. Our new data lead to new concepts about the processes that form and modify the Moho. Synthesis of this new information with estimates of the physical conditions deduced from metamorphic assemblages and the new paradigms for crustal processes afforded by plate tectonics will lead to new concepts for the origin and metamorphism of the northern Appalachians and for the subsequent breakup of the macrocontinent. Over the next decade or two, such syntheses should afford many opportunities for igneous and metamorphic petrologists, students of mineral physics, and geologists in general to participate in the development of geodynamics. I hope that Paul Ribbe will agree that big science is not all bad news: it will present us with many new opportunities to apply our skills in interpreting our data about minerals and rocks so that we can understand Earth processes.

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