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Dipping Reflectors Beneath Old Orogens: A Perspective from the British Caledonides

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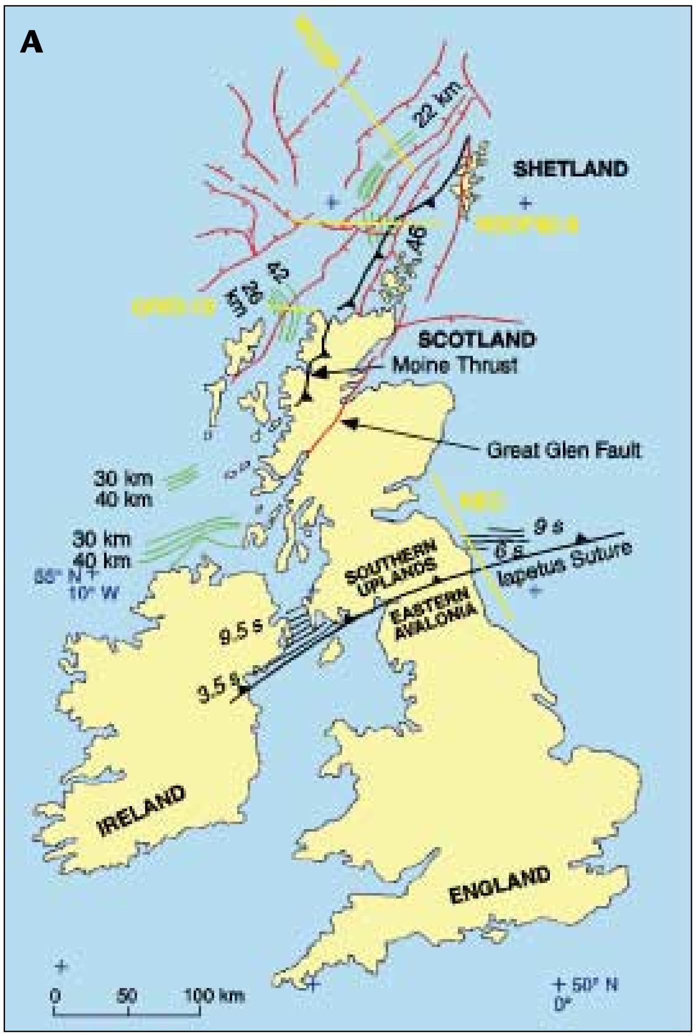

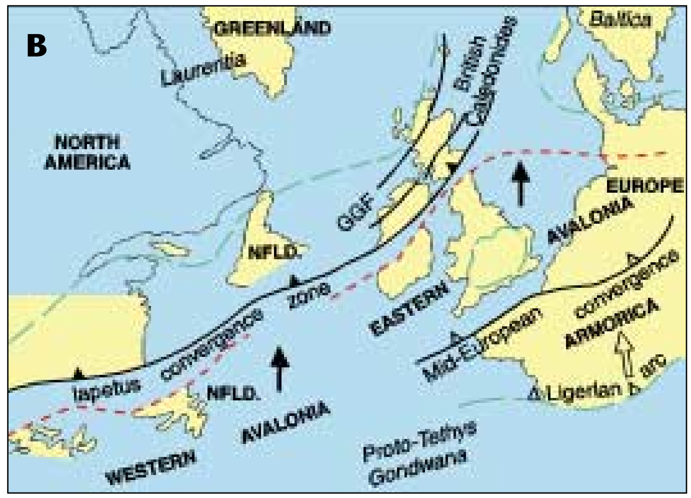

Figure 1. A: Generalized location map of the British Isles showing principal structural elements (red and black) and location of selected deep seismic reflection profiles discussed here. Major normal faults are shown between mainland Scotland and Shetland. Structural contours (green) are in kilometers below sea level for all known mantle reflectors north of Ireland, north of mainland Scotland, and west of Shetland (e.g., Figs. 2A and 5); contours (black) are in seconds (two-way traveltime) on the reflector I-I′ (Fig. 2B) projecting up to the Iapetus suture (from Soper et al., 1992). The contour interval is variable. B: A Silurian-Devonian (410 Ma) reconstruction of the Caledonian-Appalachian orogen shows the three-way closure of Laurentia and Baltica with the leading edge of Eastern Avalonia thrust under the Laurentian margin (from Soper, 1988). Long-dash line indicates approximate outer limit of Caledonian-Appalachian orogen and/or accreted terranes. GGF is Great Glen fault; NFLD. is Newfoundland.

ABSTRACT

After two decades of deep seismic reflection profiling, our understanding of dipping reflectors in the crust and upper mantle beneath old orogenic belts, and especially their relation across the crust-mantle boundary, remains incomplete. The Caledonian orogenic front (Moine thrust) and the Iapetus suture in Great Britain, two of the world's most studied compressional belts, show a consistent pattern of discrete dipping reflectors in the upper-to-middle crust, suggesting a "thick-skinned" structural style. These reflectors project downward into a pervasive zone of diffuse reflectivity in the lower crust. This zone of diffuse reflectivity corresponds to a theoretical depth interval of low strength that represents distributed shearing separating upper crustal and uppermost mantle layers of greater strength. Prominent dipping reflectors also occur within the high-strength uppermost mantle beneath the Caledonian orogen. Reflectors within the stronger upper-to-middle crust and upper mantle are not connected across the Moho discontinuity and thus seem kinematically distinct, although mantle reflectors in places appear to continue upward into the lowermost crust. Dipping crust and mantle reflectors probably originated from different geologic events: dipping reflectors in the crust first took form as thrusts during the early Paleozoic Caledonian orogeny, whereas those in the upper mantle

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have an even older history associated with an as yet unrecognized episode of subduction or Late Proterozoic rifting of the Laurentian supercontinent. Crust and mantle reflectors were likely reactivated by Mesozoic and younger North Sea rifting, which may also have produced, or at least enhanced, the diffuse reflectivity in the low-strength lower crust.

INTRODUCTION

Since its inception in 1981, the British Institutions Reflection Profiling Syndicate (BIRPS) has been accumulating deep seismic reflection data over the offshore parts of the Caledonian orogen. To date, about 17,000 km of profiles have been recorded around the British Isles. The major crustal framework structures of the Caledonian orogen, namely the Caledonian orogenic front (locally Moine thrust) and the Iapetus suture, are arguably the best studied Paleozoic orogenic features in the world, particularly from the standpoint of deep reflection data. These two structures together effectively delimit compressional deformation resulting from the Caledonian orogeny (Silurian–Early Devonian) in Britain (Fig. 1A). The goal of this report is to summarize results of our recent work on the British Caledonides by focusing on the significance of dipping reflectors, features now considered to be characteristic of compressional orogens.

The greater Paleozoic Caledonide-Appalachian orogen continues to be the focus of studies of collisional tectonics, as illustrated by the recent debate over the relation of the early Paleozoic Argentine Precordillera and related terranes in South America to the North American Appalachians (e.g., Astini et al., 1995). The well-defined reflector patterns of the crust and upper mantle for the British Caledonides provide a guide to understanding terrane boundaries in Britain as well as elsewhere. The three main problems we address are: (1) Can dipping crustal reflectors beneath the Caledonides be unequivocally linked with compressional structures at the surface, and how are compressional structures distributed deeper within the crust? (2) Does dipping reflector structure in the upper mantle beneath the Caledonides have any relation to Paleozoic or younger features in the crust above it—what really are the admissible interpretations for upper mantle reflectors? (3) Finally, we argue that the crust and upper mantle were mechanically decoupled during Caledonian compression, and that crust and mantle deformation structures beneath the Caledonides have separate origins.

DIPPING CRUSTAL REFLECTORS

Moine Thrust

The Moine thrust (Fig. 1A) is the classic structure of the Caledonide-Appalachian system, and is probably analogous to the Taconian suture in the North American Appalachians. Where it crops out in mainland Scotland, the thrust floors a thick east-dipping mylonite zone that separates metamorphic rocks of the thrust belt to the east from the less deformed Precambrian foreland and cover sequence to the west (Barr et al., 1986). Deep seismic data over the offshore projection of the thrust reveal a thick wedge of east-dipping reflections in the middle-to-lower crust (Fig. 2A). This wedge is capped by a highly coherent reflection (Fig. 2A; M-M′) that correlates with the Moine thrust (McBride and England, 1994). The thrust separates an unreflective upper crust from a highly reflective crust below. The thrust can be projected into the lower crust on the basis of weaker collinear reflection segments and by the distinct change from the eastward-dipping fabric of the wedge to a westward-dipping set of reflections immediately to the east (W-W′).

Iapetus Suture

The Iapetus suture forms one arm of the Caledonian triple convergent "junc-

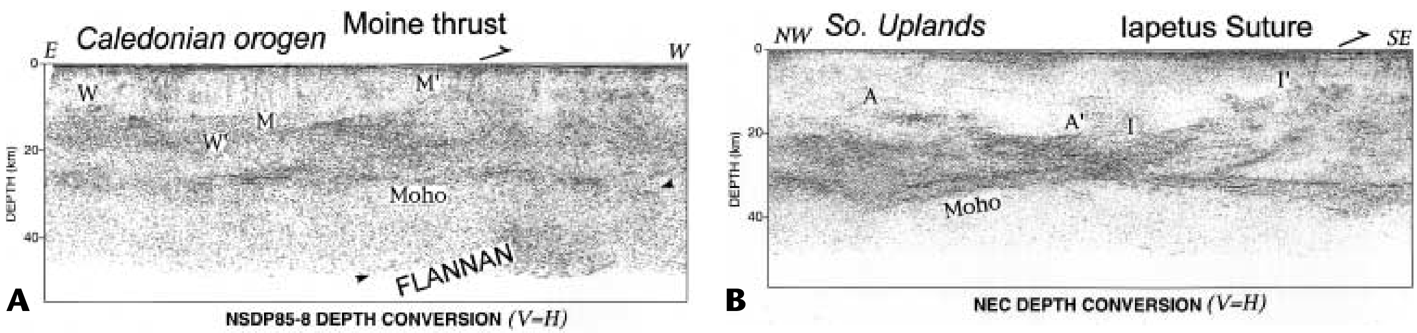

Figure 2. A: A 15° finite-difference time migration and depth conversion of Geco-Prakla NSDP85-8 seismic reflection profile (section displayed with east on left so seismic character can be directly compared to that in B). M-M′ is the interpreted Moine thrust reflector. W-W′ is an oppositely dipping reflector that appears to be cut off by M-M′. "Flannan" refers to dipping mantle reflector. B: A 15° finite-difference time migration and depth conversion of BIRPS NEC seismic reflection profile. I-I′ is a dipping reflector within the Iapetus suture. A-A′ is a weak set of subhorizontal reflectors. See Figure 1A for location. Data are displayed as variable area, no wiggle traces with no vertical exaggeration (V = H).

tion" of Laurentia, Baltica, and Gondwana (Fig. 1B). In mainland Britain, the suture separates the Eastern Avalonia terrane to the south from the Southern Uplands to the north (Fig. 1A), the farthest outboard of the Caledonian terranes accreted to Laurentia before the final closure of the Iapetus Ocean. Suturing is inferred to have been in the Middle Silurian and associated with northward subduction (Soper et al., 1992). Deep seismic profiles crossing the offshore projection of the Iapetus suture (NEC line in Fig. 1A) typically show two strong north-dipping reflectors spanning the middle crust (below and including I-I′ in Fig. 2B). The upper and northernmost reflector forms a boundary between reflective and unreflective crust. The seismic expression of the Iapetus suture is interpreted as the leading edge of Avalon crust (i.e., the footwall of the suture zone). A possible reversal of reflector dip appears farther northwest in the hanging wall of the suture zone (A-A′ in Fig. 2B), but the northwest-dipping pattern clearly dominates the crustal section and may slightly continue into the uppermost mantle, where it appears to either offset Moho reflections or merge with a northwest-dipping Moho.

Moine Thrust and Iapetus Suture Synthesis

A key point of our study is that the seismic signatures of the Moine thrust and Iapetus suture show significant similarities even though they appear to be quite different structures at the surface. Both crustal sections are dominated by a prominent dipping reflector that correlates with a metamorphic and/or terrane boundary and that divides the crust into a reflective lower section and a poorly reflective upper section. The dipping reflector acts as the leading edge of highly reflective crust which may be more widely deformed than poorly reflective crust. In each case, this dominant reflector appears to approach the Moho as a planar surface and to disrupt the Moho at intersection. The dominant and other associated dipping reflectors do not actually extend into the mantle. The continuation of the reflective wedge from the middle crust toward the Moho suggests a "thick-skinned" model for the Caledonian orogen, with thrusts imbricating the footwall rather than a single decollement separating upper and lower plates. If we interpret these observations in terms of deformation in a compressional zone, then the dominant reflector becomes a discrete thrust or shear zone, and the underlying reflectivity represents distributed and disordered deformation that continues to the base of the crust where it abruptly disappears. A principal difference between the crust beneath the Moine thrust and the Iapetus suture is the prominence of a "bivergent" (i.e., interpreted thrusts dipping in opposing directions) pattern of dipping reflectors in the Moine thrust section (Fig. 2A) compared with the relative absence of a bivergent pattern in the Iapetus suture section (Fig. 2B).

A finite-difference geodynamic model (Quinlan et al., 1993) formulated to explain dipping reflectors beneath orogens predicts a bivergent pattern that develops during a single deformation phase. This pattern forms above a stress discontinuity where the subducting crust bends downward as it detaches from its mantle (Fig. 3). Such models are potentially useful in linking observations of dipping crustal reflectors with mantle subduction polarity. Beneath the Moine thrust, a bivergent pattern similar to that in the model is observed (W-W′ and M-M′ in Fig. 2A). A problem is that this pattern may simply represent two distinct deformation episodes (W-W′, being older, is crosscut by the Moine thrust pattern). For the Moine thrust section where the dominant reflector dip is to the east, the model predicts that westward subduction occurred beneath Scotland (cf. Figs. 2A and 3). As yet, no such subduction has been inferred from surface geology (Barr et al., 1986). Near the Iapetus suture (I-I′ in Fig. 2B), no clear bivergence is observed, although the reflection data show one set of discordant reflectors (A-A′) that appears to intersect the dominant dipping Iapetus suture pattern. Following the model (Fig. 3), the predominance of northwest-dipping crustal reflectors would be associated with southeastward subduction; however, the available geologic evidence has been used to argue in favor of northward subduction (Soper et al., 1992).

In summary, the crustal sections underlying the two principal framework structures of the Caledonian orogen have a similar seismic signature. This similarity points toward a unified explanation in which both structures have a mainly thick-skinned deformation style modified by thrust imbrication. The thrust vergence directions inferred from the seismic data

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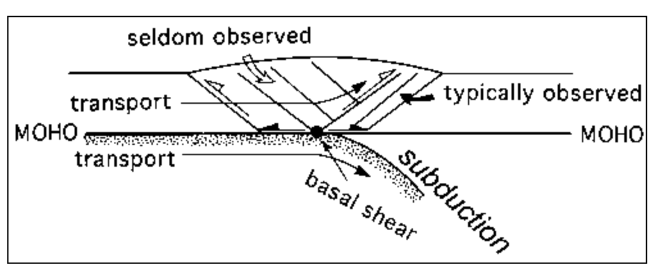

Figure 3. One-stage geodynamic model (from Quinlan et al., 1993) representing two domains of dipping crustal reflectors interpreted as thrust faults associated with subducting lithosphere. Only one domain is typically observed in the British Caledonides as indicated (see particularly Fig. 2B). As subduction proceeds to the right, mantle lithosphere is detached from the crust. The black circle gives the position on the top of the down-going plate where the mantle of the left plate detaches and is underthrust. The direction of the dominant thrust vergence is the same as that of material transport.

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indicate transport of crustal material away from the interior of the orogen (i.e., northwest for Moine thrust, southeast for Iapetus suture; Figs. 1A and 4). In summary, a single-phase geodynamic model correctly predicts key aspects of the seismic observations; however, linking the dipping reflector pattern in the crust to subduction in the mantle remains a problem. Our next step must be to intensify study of reflectivity in the upper mantle and show how it is, or is not, structurally linked with crustal reflectivity.

DIPPING MANTLE REFLECTORS

One of the world's most remarkable regions of reflective upper mantle (Fig. 1A) lies beneath the British Caledonides (Flack et al., 1990). New industry seismic profiles and reprocessed older profiles have recently improved our knowledge of the Flannan mantle reflectors (Fig. 5), better constraining their regional distribution and origin. We have pursued a working hypothesis that the northern Scottish mantle reflectors (currently mapped as an east-plunging antiform north of mainland Scotland and a synform west of Shetland; Fig. 1A) and the occasional reflectors from seismic lines north and west of Ireland (Fig. 1A) are correlative or at least closely related. Comparison of the sections in parts A and B of Figure 5 shows that the expression of this mantle reflector and its geometrical relation to the Moho vary considerably along strike. Northwest of the Scottish mainland (west end of section in Fig. 5A), the reflector continues from the uppermost mantle into the lower crust and marks a disruption or offset of the Moho. Although other workers have argued that this reflector is either a Mesozoic normal fault or a Caledonian thrust, it does not consistently follow either Mesozoic or younger normal fault trends, or Caledonian structural trends. On none of the available profiles can continuity of normal faults nor thrusts down into the upper mantle be seen, despite the fact that the Moine and other Caledonian thrusts, as well as major basin-bounding normal faults, commonly dip in the same direction as the mantle reflector.

The key point of our observations is that reflectors in the crust are discontinuous with and spatially unrelated to reflectors in the upper mantle and thus have distinct origins. We suggest that although the mantle reflectors were probably reactivated by Phanerozoic tectonism, they actually originate from a Precambrian tectono-thermal event. The complex shape of mantle reflectors in map view (Fig. 1A) may be related to subsequent deformation episodes. The multistrand nature of the reflection on some profiles (Fig. 5A) may express multistage reactivation of a zone of shearing. Two proposed explanations for a pre-Caledonian origin are that these reflectors represent (1) a relict subduction zone (Warner et al., 1996), or (2) extensional shearing within the upper mantle produced during Neoproterozoic rifting of the Laurentia-Baltica supercontinent (McBride et al., 1995). Support for pre-Caledonian subduction comes from the postulated accretion of at least one island arc onto the Laurentia-Baltica supercontinent at 1.8 Ga (Dickin, 1992). Alternatively, on the basis of parallelism between the trend of mantle reflectors and the old Laurentian margin (Fig. 1B), the mantle reflectors contoured in Figure 1A may be associated with Neoproterozoic rifting (McBride et al., 1995). Current models of continental rifting (e.g., Torske and Prestvik, 1991) predict the continuation of normal faults from the upper crust into the mantle as extensional shear zones that could be preserved as zones of high impedance contrast. It is difficult to favor conclusively either a subduction or a rifting hypothesis at this time, although both hypotheses postulate a zone of shearing or detachment in the mantle. Even though the Iapetus suture is associated with known subduction, no mantle reflectors have been observed anywhere on the profiles that cross it. Thus, it is clear that subduction need not produce mantle reflectors that are preserved for hundreds of millions of years after the event.

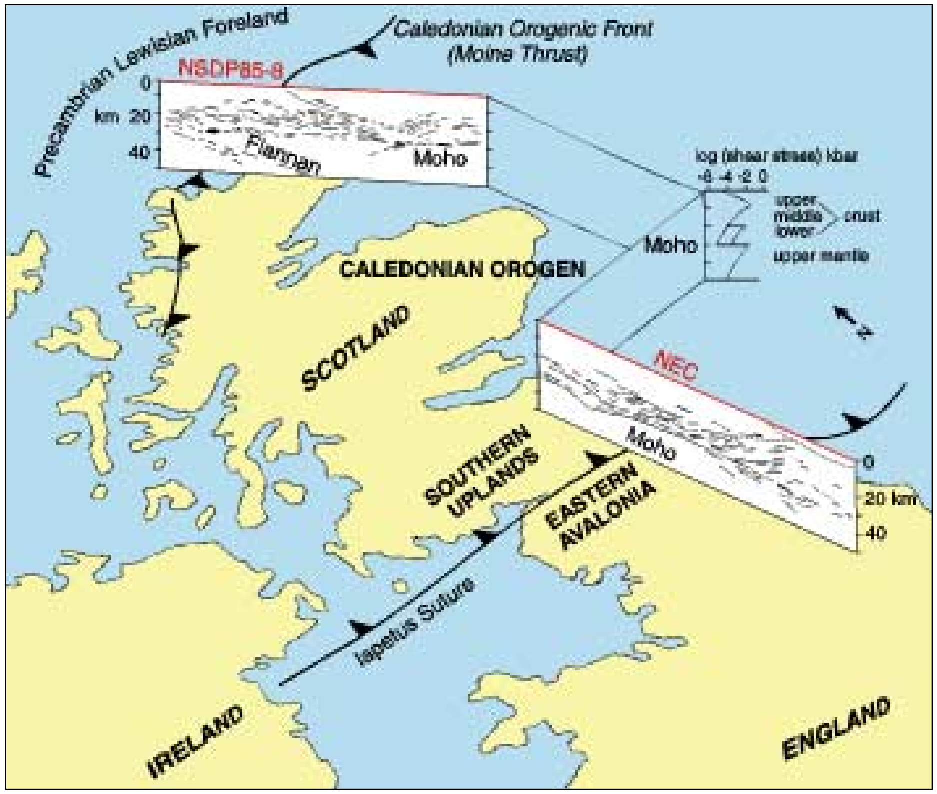

Figure 4. Simplified schematic drawings of NSDP85-8 and NEC seismic reflection profiles showing their positions relative to the surface traces of the Caledonian orogenic front (locally Moine thrust) and the Iapetus suture. Arrows on profiles indicate interpreted thrust vergence. The two seismic sections are shown referenced to a theoretical shear stress vs. depth curve for an idealized continental crust and mantle lithology (from Meissner and Kusznir, 1987) and a surface heat flow of 70 mW/m^2, typical for a Paleozoic orogen (alternative curve for lower crust assumes abrupt mid-crustal shift from acidic to dry mafic mineralogies).

STRAIN PARTITION IN CALEDONIAN LITHOSPHERE

The above discussion of crust and mantle structure, in which Caledonian-age thrusts and mantle reflectors are spatially unconnected, suggests distinct crust and upper mantle strain patterns. Rheological models of the crust and upper mantle, which assume an increasing mafic and decreasing quartz mineralogy with depth and a typical orogenic geotherm (e.g., Meissner and Kusznir, 1987), predict strength maxima in the mid-crust and just beneath the Moho for a constant applied stress (Fig. 4). Using these models, the low-strength zone in the lower crust corresponds to the zone of highest and most coherent reflectivity. This observation is consistent with interpreting these reflective zones as resulting from shear, and it provides an explanation for the concentration of deformation-related reflectivity in the middle and lower crust (cf. Kusznir and Matthews, 1988). With elevated temperature in the mid-to-lower crust, one would expect a partially ductile

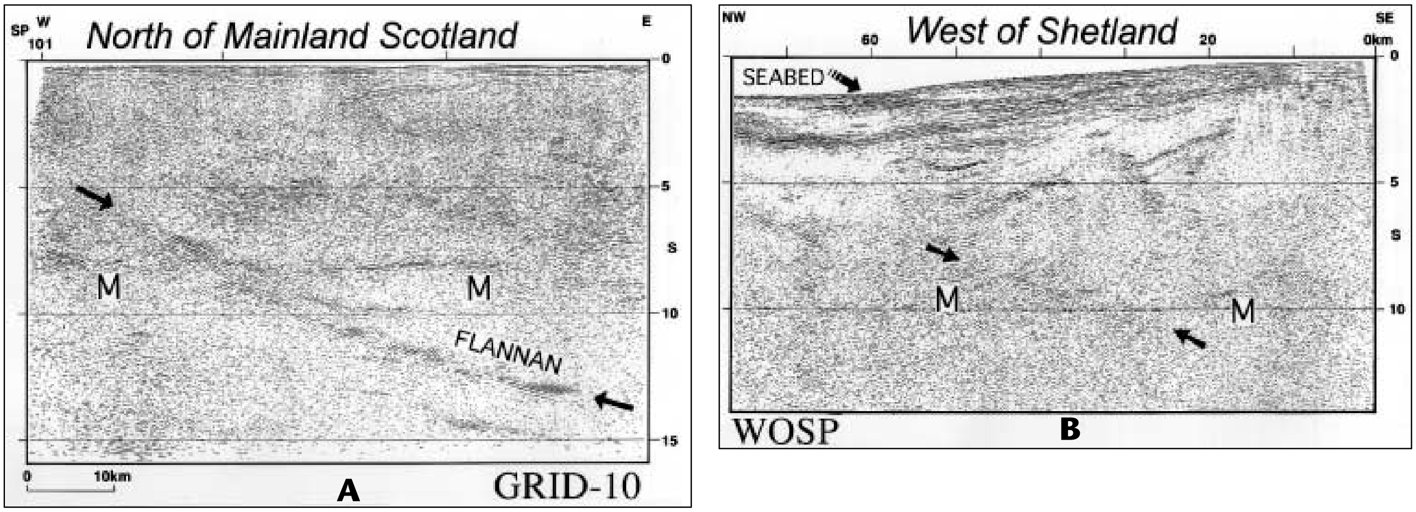

Figure 5. A 15° finite-difference time migration of BIRPS GRID-10 and the WOSP (West Of Shetland Profile) reflection seismic sections. See Figure 1A for location. Arrows indicate mantle reflectors (e.g., Flannan) shown as contours in Figure 1A. M is reflection from Moho discontinuity. Data are displayed as variable area, no wiggle trace sections with no vertical exaggeration for a time-depth conversion velocity of 6 km/s.

rheology, so that compressional deformation would develop as broad ductile shear zones rather than discrete brittle faults. The contrasting rock types necessary for the high-amplitude reflectivity could be produced either by deforming reflective material into elongated shapes that are optimum for strong reflection, juxtaposing layers with distinct impedance (seismic velocity and density), or creating a new high-reflectivity layer by internal deformation (e.g., mylonitization).

High-strength zones in the upper-to-middle crust and the uppermost mantle are characterized by a substantial decrease in reflectivity relative to the lower crust, almost to the point of being acoustically blank. Reflectivity, where it does exist within these zones, consists of a single bright reflection or narrow concentrations of reflections. The localization of shear stress maxima and minima around the Moho underscores the concept of mechanical decoupling accompanied by a change in deformation style near this boundary and is in harmony with the observation that dipping reflectors in the crust and mantle are discontinuous across the Moho. If the uppermost mantle is stronger than the crust (Fig. 4; Meissner and Kusznir, 1987; Cook and Varsek, 1994), stress-induced failure will occur at different times and rates in the crust and mantle. This means that the points of failure will not necessarily be linked, and that deformation structures will not match across the crust-mantle boundary.

CONCLUSIONS

The large set of reflection profiles from the Caledonide orogen around Britain reveals a "thick-skinned" structural style for the upper-to-middle crust. This style is expressed by a coherent planar reflector dipping toward the interior of the orogen which divides the crust into upper poorly reflective and lower highly reflective zones. Although a bivergent reflector pattern appears occasionally, as predicted by recent geodynamic models, a univergent reflector pattern best characterizes each side of the Caledonides. As such, dipping reflector patterns cannot yet be reliably linked to subduction polarity as suggested by the models. Univergent reflector patterns are also well developed in the upper mantle where they dip in the same direction as the Moine and other Caledonian-age thrusts. Because these mantle reflectors are unrelated to Phanerozoic deformation patterns, either in plan or cross-sectional view, we suggest a Precambrian origin for them. The complex mantle reflector contour pattern seen in Figure 1A probably arose from subsequent Caledonian compression or later extension associated with North Sea rifting that probably reactivated the mantle reflectors. A simple hypothetical Caledonian stress vs. depth relation indicates that discrete reflectors appear in strong upper and middle crustal and mantle layers, and that distributed reflectivity characterizes low-strength lower crust. The pronounced contrast of reflectivity across the crust-mantle boundary is consistent with this boundary acting as a detachment. Dipping reflectors in the crust and upper mantle are discontinuous across this boundary and must have had kinematically different origins.

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REFERENCES CITED

Astini, R. A., Benedetto, J. L., and Vaccari, N. E., 1995, The early Paleozoic evolution of the Argentine Precordillera as a Laurentian rifted, drifted, and collided terrane: A geodynamic model: Geological Society of America Bulletin, v. 107, p. 253–273.

Barr, D., Holdsworth, R. E., and Roberts, A. M., 1986, Caledonian ductile thrusting in a Precambrian metamorphic complex: The Moine of northwestern Scotland: Geological Society of America Bulletin, v. 97, p. 754–764.

Cook, F. A. and Varsek, J. L., 1994, Orogen-scale decollements: Reviews of Geophysics, v. 32, p. 37–60.

Dickin, A. P., 1992, Evidence for an Early Proterozoic crustal province in the North Atlantic region: Geological Society of London Journal, v. 149, p. 483–486.

Flack, C. A., Klemperer, S. L., McGeary, S. E., Snyder, D. B., and Warner, M. R., 1990, Reflections from mantle fault zones around the British Isles: Geology, v. 18, p. 528–532.

Kusznir, N. J., and Matthews, D. H., 1988, Deep reflections and the deformational mechanics of the continental lithosphere: Journal of Petrology, Special Lithosphere Issue, p. 63–87.

McBride, J. H., and England, R. W., 1994, Deep seismic reflection structure of the Caledonian orogenic front west of Shetland: Geological Society of London Journal, v. 151, p. 9–16.

McBride, J. H., Snyder, D. B., Tate, M. P., England, R. W., and Hobbs, R. W., 1995, Upper mantle reflector

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Geology and Geologists in the Former Soviet Union: Opportunities for Interaction

These three articles give us a glimpse of new possibilities for scientific interchange made possible by political change — the breakup of the Soviet Union

The Life of Geologists in the Former Soviet Union

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Geologists in the former Soviet Union are now having hard times. While the average salary of a geologist is less than US$100 per month, the prices for food, clothes, furniture, and housing are nearly the same as in the United States. Moreover, a helicopter is essential for field work in much of Russia, but chartering one costs about $1000 per hour, which is about the same as, or more than, in the United States. However, because they like their work and do it very well, Russian geologists continue to work, in spite of these difficulties.

There are various groups of geologists in Russia—geological survey scientists who deal with regional studies and perform geologic mapping, mining geologists, and geologists in academic institutes and universities. I have worked my entire life in academic institutes, but I have also taught at the universities and maintained close contacts with geologists from the geological survey. Thus, I know about the lives of all the groups of geologists in Russia.

I live and work in the town of Yakutsk, the capital of the Sakha Republic (Yakutia), a part of the Russian Federation. Yakutia is a vast area in northeast Siberia covering about 3.3 million km^2 and having a population of about 1 million. About 35% of the population are Yakuts and other native peoples; the remainder are Russians. The republic has its own president and government. Our republic spans several natural zones, including tundra along the shores of the Arctic Ocean, a mountainous eastern part, and a vast boggy lowland in the west. The main rivers flow into the Arctic Ocean and cross Yakutia from south to north; they are the primary routes for shipping. The Yakutian climate is very severe; winter lasts for 7–8 months, and temperatures reach minus 34 to minus 50 °C. Summer is brief (2–3 months) and hot (30–40 °C). Yakutsk is a city of about 200,000 and hosts governmental and cultural institutions, Yakut State University, and the Yakut Science Center of the Siberian Division of the Russian Academy of Sciences, which includes eight scientific institutes. I work in the Yakutian Institute of Geological Sciences and am concurrently a professor in the geology department of the university.

Russia, especially Siberia, is rich in mineral resources. There are numerous mineral deposits in Yakutia, discovered because of the work of many geologists. Most important are deposits of diamonds, gold, coal, rare earth elements (REEs), iron, natural gas, and oil on the Siberian platform, and gold, silver, tin, antimony, zinc, lead, coal, rare metals, REEs, and others in the Mesozoic orogenic belt in eastern Yakutia. It is possible that additional large deposits have yet to be discovered. Transportation and technology difficulties make most of these deposits, other than diamonds, unprofitable.

At present, geologic maps completed in the early 1970s, at a scale of 1:200,000, represent almost the entire territory of Russia. These maps have long been secret, and although many have now been issued, they remain unavailable to foreign geologists. This work would not have been accomplished without specialized schools and institutes, not only in Moscow and Leningrad, but also in most of the large cities of Siberia and the Russian Far East. In the course of this work, a whole generation of specialists in regional geology grew. A representative of that generation was Lev Zonenshain. He devoted much of his life to geologic mapping of various regions of the former USSR and developed into a scientist well-known even in America.

During the mapping in the 1950s and 1960s, the major tectonic structures were interpreted and large mineral deposits were discovered; for example, oil and gas fields in western Siberia, and diamonds in Yakutia. The theoretical basis of geologic investigations during that time was the geosynclinal concept. It was within this framework that the geology was interpreted and many great discoveries were made; this explains, in part, why the concept is still supported by many Russian geologists. But the main reason for the conservatism of Russian workers is intellectual isolation. For decades under Soviet power, science in the former USSR, including geology, was forcibly isolated from the rest of the world. Many of the new scientific ideas that appeared in the West were ignored as being bourgeois and alien to progressive Soviet science. Great efforts were made to develop something of our own that differed from western ideas. For this reason, the orthodox fixist interpretation of the geosynclinal concept remains popular among Russian geologists. An example of such ideas is the "deep fault" concept, which was incomprehensible to western geologists. Lev Zonenshain did much to popularize plate tectonics in the former Soviet Union, but it is still not generally accepted.

In the early 1970s, it was decided to compile a geologic map of the entire USSR at a scale of 1:50,000. This was to begin a new stage in the geologic study of the country and to lead to new discoveries. Maps at this scale are now available for most of the country, but most of them are simply enlarged copies of the earlier 1:200,000 maps; the hoped-for advances in geology did not occur. I believe that the reason for this lack of progress was, again,

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Dipping Reflectors *continued from p.5*

structure and origin beneath the Scottish Caledonides: Tectonics, v. 14, p. 1351–1367.

Meissner, R., and Kusznir, N. J., 1987, Crust viscosity and the reflectivity of the lower crust: Annales Geophysicae, v. 5, p. 365–374.

Quinlan, G., Beaumont, C., and Hall, J., 1993, Tectonic model for crustal seismic reflectivity patterns in compressional orogens: Geology, v. 21, p. 663–666.

Soper, N. J., 1988, Timing and geometry of collision, terrane accretion and sinistral strike-slip events in the British Caledonides, *in* Harris, A. L., and Fettes, D. J., eds., The Caledonide-Appalachian orogen: Geological Society of London Special Publication 38, p. 481–492.

Soper, N. J., England, R. W., Snyder, D. B., and Ryan, P. D., 1992, The Iapetus suture zone in England, Scotland and eastern Ireland: A reconciliation of geological and deep seismic data: Geological Society of London Journal, v. 149, p. 697–700.

Torske, T., and Prestvik, T., 1991, Mesozoic detachment faulting between Greenland and Norway: Inferences from Jan Mayen Fracture Zone system and associated alkalic volcanic rocks: Geology, v. 19, p. 481–484.

Warner, M., Morgan, J., Barton, P., Morgan, P., Price, C., and Jones, K., 1996, Seismic reflections from the mantle represent relict subduction zones within the continental lithosphere: Geology, v. 24, p. 39–42.

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