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Seismic reflection response of folded structures and implications for the interpretation of deep seismic reflection profiles

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Abstract

Seismic reflection characteristics of several common folded structures have been investigated by forward synthetic modeling in order to interpret correctly the seismic data from ancient and modern orogenic belts. The studied folds include single-order open folds, close folds and asymmetric inclined folds as well as multi-order folds. The results show that complex folded structures and particularly those in deep crust cannot be accurately imaged by conventional 2D reflection profiling. It is possible that widely observed subhorizontal, discontinuous reflections in the continental crust of compressional folded belts do not necessarily correspond to subhorizontal compositional lamination. Multi-order folded structures may equally enable the formation of such reflections. Furthermore, trains of asymmetric inclined folds produce straight, discontinuous, dipping reflections that are potentially misinterpreted as thrusting faults or shear zones. Thus structural geologists must be extremely cautious when trying to convert directly seismic reflection sections to geological profiles for the continental crust.

Keywords: Folds; Seismic reflections; Continental crust; Tectonic deformation

1. Introduction

One of the most important impetuses for seismic profiling is to investigate the structure and composition of the crust as a function of depth from velocity and reflectivity information. In the last three decades, huge seismic reflection data sets (e.g., LITHOPROBE, COCORP, ECORS, BIRPS and DEKORP) have been collected over all the continents in the world (Pfiffner et al., 1991; Martignole and Calvert, 1996; Cook et al., 1999; and many others). However, there are still difficulties and pitfalls in the geological interpretation of seismic profiles due to various inherent limitations associated with the seismic reflection technique such as the potential artefacts related to near surface phenomena, multiple reflections, finite frequency effects, steeply dipping structures, lateral variations of velocity, changes in orientation of the acquisition profile, or simply to practical limitations in the numerical processing tools or acquisitions. Some limitations can be partly overcome with costly 3D seismic exploration that consists of several parallel receiver lines and orthogonal shot lines. Nevertheless such high quality 3D crustal-scale seismic images are unavailable for most tectonically interesting regions because most 3D work has been and is still devoted to detailing geological features of the shallow crust in oil fields in order to eliminate unnecessary wells and to discover more hydrocarbons. The purpose of this paper is to discuss, from a structural geologist's point of view, seismic responses of several canonical folded structures that may affect the interpretation of deep seismic reflection data in deformed regions. It is emphasized that incautious geologists may make some potential misinterpretation without keeping in mind the aforementioned limitations for the seismic reflection profiles in the regions of compressional orogenic belts.

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Folds, which are seen on all scales from the microscopic to the regional, are probably the most common geological structures in the continental mountain belts of various ages (e.g., Burg et al., 1994; Pfiffner et al., 2000). An in-depth understanding of seismic response of various folded structures is extremely important for correct interpretation of the seismic profiles in terms of geology and tectonics. Several important questions need to be answered. For example: Can folds with complex geometry be correctly imaged by conventional reflection techniques? If not, what are the reflection characteristics of folded structures in term of their geometry (e.g., shape, symmetry, orientation and tightness)? Why are folds hardly observed in the seismic images of crystalline crust although they are common structural features in metamorphic terrains? Is the seismically layered structure on many deep crustal reflection profiles a reality or an artefact of complex response of deformed rocks? Do the folds produce some types of seismic images that do not look like they have come from the folds? Can the folds result subhorizontal, laterally discontinuous reflections similar to those widely observed in crustal reflection profiles? To address these questions, we carried out a study on seismic reflections of multilayer folds using forward synthetic modeling. The preliminary results help constrains on the interpretation of continental reflection data, especially in the crystalline crust where complex folding structures of various types and scales are prevailing.

2. Methodology

Seismic response of folded structures, which are too complicated to be amenable to theoretical treatment, currently can be investigated using two methods. The first is a direct physical modeling of miniature artificial models or samples using ultrasonic techniques (e.g., Melia and Carlson, 1984; McDonald et al., 1983). The physical models are generally two-component solid, multi-layer, folded media (e.g., glass and epoxy) with shape and dimensions suitable for laboratory measurements. For the simplicity, each component should be elastically isotropic so that the observed reflections are entirely due to the oriented folds rather than to the anisotropic properties of the constitutive materials. A number of physical models needs to be constructed by varying media parameters such as volume fraction, layer thickness, shape and style of the folds in order to understand their influences on the seismic reflection features. One of the technical problems associated with making the physical models, which is difficult to resolve, is to eliminate intralayer and interlayer pores and to ensure the interlayer bonding. Although it is unnecessary to perform the experiments under high confining pressures, some confining pressures (say 10–20 MPa) are required in order to prevent improper contacts along the interfaces in the samples. This method is time consuming and expensive.

The second method is two- or three-dimensional (2D or 3D) reflection modeling using Kirchhoff algorithm (i.e., INSIGHT software package) and acoustic finite difference approximation (i.e., PROMAX software package). The Kirchhoff algorithm is relatively slower, but the results are more accurate for steeper dips. In contrast, the finite difference algorithms produce poorer results for dips higher than 40°. The commercial INSIGHT software package, which was developed by ITA (Inverse Theory and Applications, Inc.), has been widely used in the data processing of the Canadian LITHOPROBE project (e.g., Long and Salisbury, 1996; Ji et al., 1997). Thus, the INSIGHT software package was used in our forward synthetic modeling.

As it is almost impossible to test all of the folding varieties, the synthetic seismograms were calculated for only four common types of folds: (1) up-right open folds (Fig. 1a); (2) up-right close folds (Fig. 1b); (3) inclined asymmetrical folds (Fig. 1c); and (4) multi-order folds in which large first-order folds include small second-order folds in their limbs and hinge zones (Fig. 1d). In each case, three homogeneous (isotropic) folded layers of high impedance are embedded in a homogeneous (isotropic) matrix of low impedance. For simplicity, all the studied folds are assumed to be cylindrical with horizontal axes so that all reflections that occur in the seismic line have their origin within a vertical plane containing that line. For trains of non-cylindrical folds or plunging folds, however, all reflections whose origins are out of the vertical plane cannot be recorded properly by 2D seismic surveys.

To simulate the in-situ geological conditions in metamorphic terrains, the velocities and densities of these two materials are assigned to equal the mean values of amphibolite and granitic gneiss at 100 MPa, that is, $Vp = 6.6$ km/s, $\rho = 2.9$ g/cm^3 for high impedance layers and $Vp = 6.1$ km/s, $\rho = 2.6$ g/cm^3 for low impedance matrix (Ji et al., 2002). It should be pointed out that the contrast of acoustic impedance between the layers is not very significant on the results since our objective is to image the geometry rather than the absolute amplitude behaviour. However, the large velocity contrast may exaggerate the disruption of the seismic wavefront in some, but not all types of fold geometry where the layer thickness varies along the seismic line. The seismic profile is chosen to be at right angles to the fold's axes so that the corrected seismic image will show the true dip of the structure. The dimension of the model is 5 km in horizontal distance and 5 km in depth in order to simulate real reflection experiments in metamorphic terrains such as the Canadian Grenville Province. The three folded layers are located in the middle of the model. The wavelength (crest to crest) of the folds is about 850 m while the amplitude (vertical distance between crest and trough) varies from model to model in order to control the dips of the fold limbs. In the calculations, the trace interval is 25 m. Kirchhoff prestack time migration method was used for calculating the migrated sections mainly for two reasons: (a) the quality of poststack migration is generally poor in areas of complex structure, and a good way to solve this problem is prestack migration; and (b) the Kirchhoff method is the most widely used crustal-scale seismic migration method because it is easy to implement, can handle steep dips, and is computationally efficient and accurate in a medium with vertical velocity variations. The wavelet frequency used is 100 Hz. The reflection characteristics of different types of folding structures and their critical controlling factors and the potential ambiguity in the geological interpretation of seismic profiles are then drawn out by comparing the migrated synthetic sections with the input reflectors.

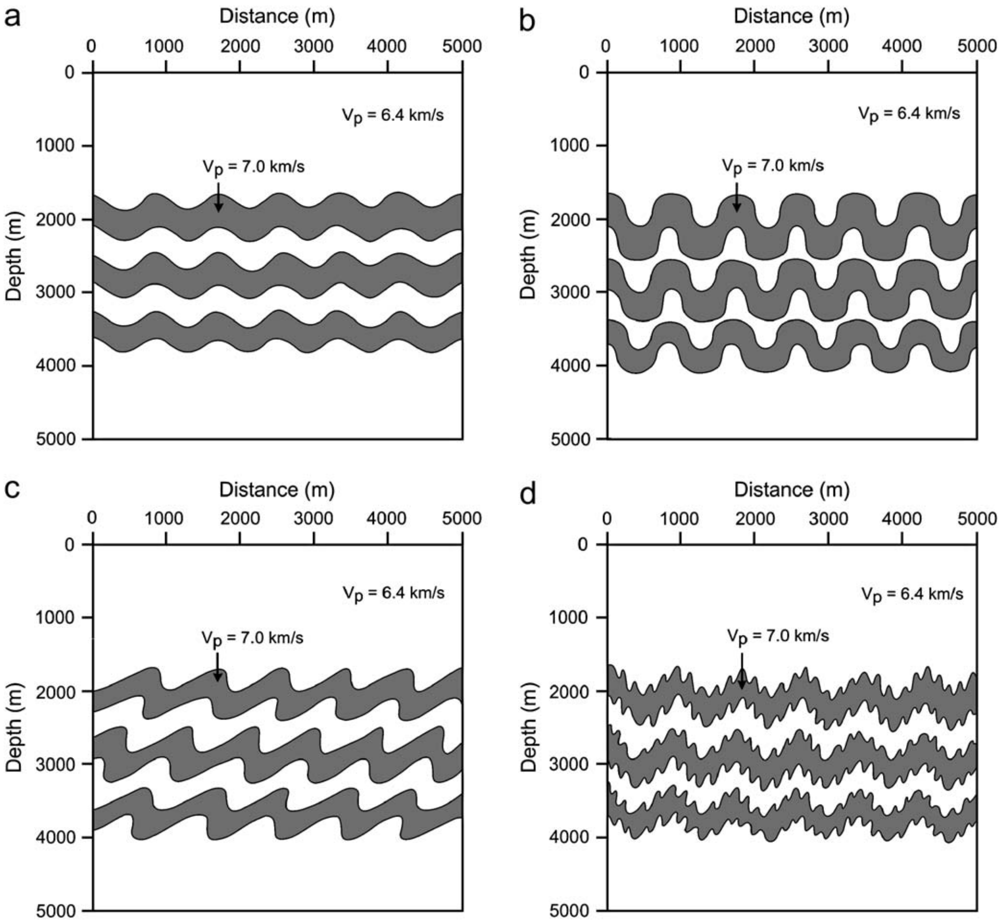

Fig. 1. Four types of folds studied by numerical modeling: (a) up-right open folds; (b) up-right close folds; (c) inclined asymmetrical folds; and (d) multi-order folds.

3. Results

Modeling results for four common types of folds (i.e., up-right open folds, up-right close folds, inclined asymmetrical folds, and multi-order folds) are demonstrated in Figs. 2–5. Both non-migrated and migrated seismic sections are shown for each type of folds. The migrated section differs substantially from its unmigrated counterpart. On the unmigrated seismic sections, dipping reflectors are distorted by being lengthened and spatially and temporally displaced, with higher dip angles being more affected. Clearly, non-migrated seismic sections bear no likeness with their in-put models, indicating that the folding geometry cannot be accurately imaged by the non-migrated section. In other words, non-migrated seismic sections give a distorted picture of reflector geometry. The distortion can be even larger in the lower crust and upper mantle where reflections may occur many kilometres from their true position on unmigrated stack sections (Calvert, 2004). Hence any geological interpretation based on non-migrated seismic reflection sections (e.g., Calvert and Clowes, 1990; Varsek and Cook, 1991; Pfiffner et al., 1991) is very speculative and almost inevitably misleading.

The comparison between the in-put model and its corresponding migrated section provide basic information on the reflection characteristics of the folds. As shown in Fig. 2b, the geometrical shape of the up-right, open folds (Fig. 1a) can be correctly imaged only for the uppermost folded layers. The deeper folded layers manifest in the migrated section as a band of laterally short reflections. The phenomenon that the top of the model is better imaged than the bottom of the model results most likely from the complex wave propagation through the folded media, the latter is not completely accounted for during the prestack Kirchhoff time migration. This phenomenon can be partially eliminated using prestack depth migration method that does not have lateral velocity variation limitations. Although the prestack depth migration has been used in the petroleum industry to generate images of the structures around salt diapers in the shallow crust, it has rarely been employed to the crustal-scale seismic profiling (Bouzidi et al., 2002). In other words, almost all the crustal images available in the literature, which have been interpreted in terms of geology and tectonics, were obtained from 2D time migration rather than depth migration.

The up-right close folds (Fig. 1b) cannot be correctly imaged by the prestack Kirchhoff time migration and their steeply dipping limbs are either entirely or partially missing from the stacks, leaving only the crests and troughs to form a series of semi-continuous subhorizontal reflections

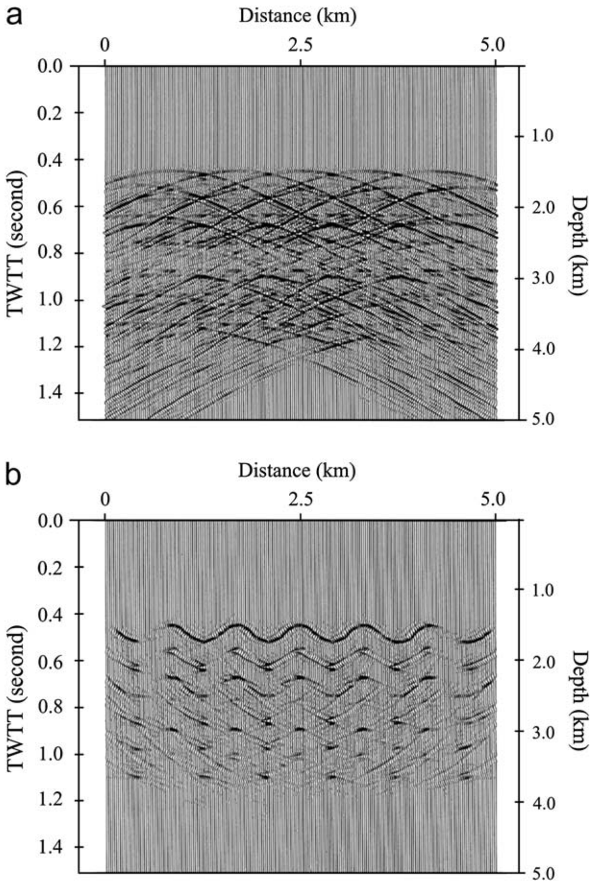

Fig. 2. Unmigrated (a); and migrated (b) seismic sections for up-right open folds shown in Fig. 1a. TWTT: two-way travel time.

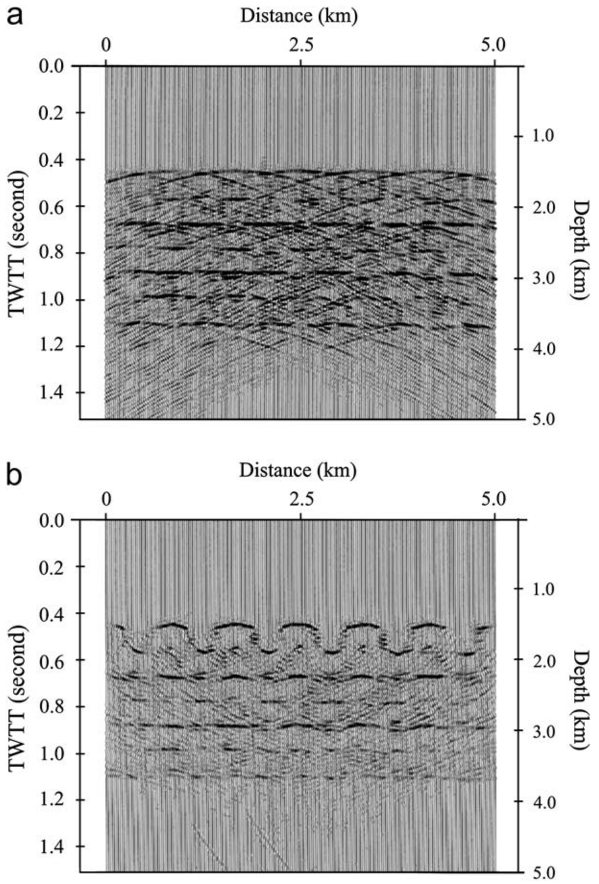

Fig. 3. Unmigrated (a); and migrated (b) seismic sections for up-right close folds shown in Fig. 1b. TWTT: two-way travel time.

(Fig. 3b). The deeper folded layers are always more poorly mapped than the upper ones. For the inclined asymmetrical folds (Fig. 1c), their near-vertical limbs cannot be seismically imaged while their gently dipping limbs produce a band of relatively straight, discontinuous, dipping reflections (Fig. 4b). For the multi-order folds with complex geometry (Fig. 1d), there is no resemblance between the migrated seismic section (Fig. 5b) and its in-put model (Fig. 1d). Complex folds are structures where the seismic reflection technique records 'no-data' in these steeply-dipping limbs and consequently reliable reflection migration becomes impossible. The forward synthetic modeling suggests that the seismic reflections do not map correctly the folded reflector shape, making the unambiguous interpretation of stacked data difficult. Clearly, imaging folded structures in metamorphic terrains remains a challenge today for reflection seismology.

4. Discussion

The seismic reflection technique is the most powerful of the methods used to image the in-situ geological nature of the continental crust. In the last three decades, huge seismic data sets (e.g., LITHOPROBE, COCORP, ECORS, BIRPS and DEKORP) have been collected over all the continents in the world, revolutionizing our understanding of continental composition, structure and evolution (e.g., Martignole and Calvert, 1996; Cook et al., 1999; Klemperer and BIRPS Group, 1987). The most important contribution of the crustal reflection studies is the discovery of high reflectivity in the deep continental crust and the recognition of distinct reflectivity patterns in the different tectonic regimes (e.g., Brown, 1987; Meissner et al., 1991; Mooney and Meissner, 1992). Young extensional middle and lower crusts are usually strongly reflective with multiple subhorizontal sets of reflections that terminate at the top of a seismically transparent upper mantle (e.g., Klemperer and BIRPS Group, 1987). Compared with young extensional regions, more complex reflection patterns consistent with pervasive thrusting and indentation are associated with compressional orogens. Precambrian regions show pronounced subhorizontal, laterally discontinuous reflections within the middle and lower crust (e.g., Martignole and Calvert, 1996; Ji et al., 1997; Cook et al., 1999).

There are three major hypotheses for the origin of the enigmatic subhorizontal, discontinuous reflections in the lower crust (Warner, 1990): (1) the presence of free aqueous fluids in the deep crust with stratified porosity (e.g., Klemperer and BIRPS Group, 1987; Holbrook et al., 1991); (2) subhorizontal shear zones, mylonitic zones or fabrics caused by ductile shearing (e.g., Passchier, 1986; Holbrook et al., 1991; Ji et al., 1997); and (3) the presence of mafic sills and layered intrusions

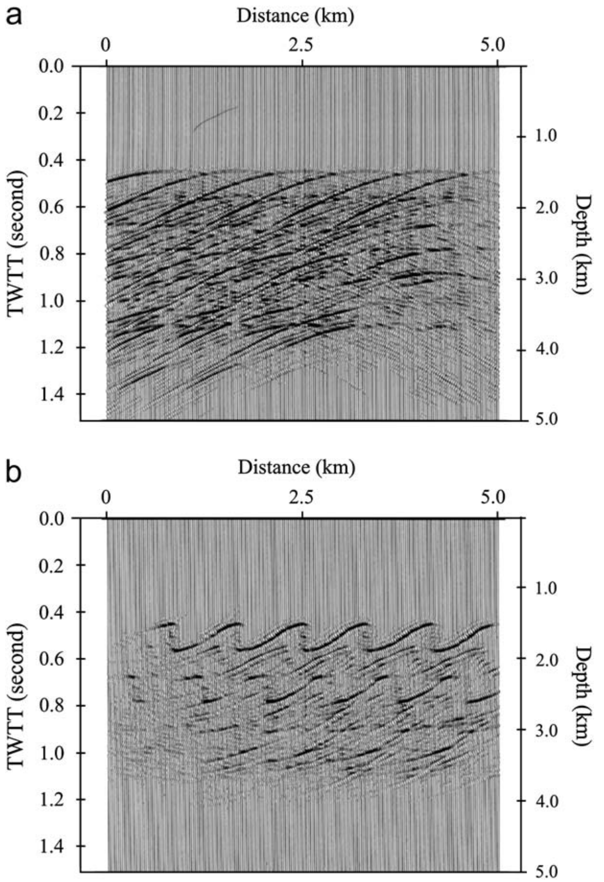

Fig. 4. Unmigrated (a); and migrated (b) seismic sections for inclined asymmetrical folds shown in Fig. 1c. TWTT: two-way travel time.

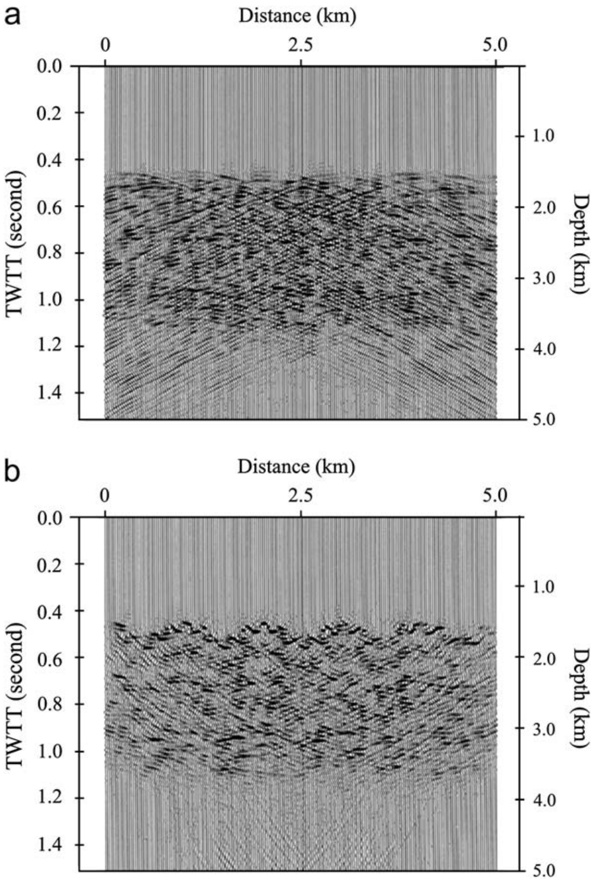

Fig. 5. Unmigrated (a); and migrated (b) seismic sections for multi-order folds shown in Fig. 1d. TWTT: two-way travel time.

associated with underplating or partial melting in the upper mantle (e.g., Deemer and Hurich, 1994; McBride et al., 2004). However, so far there has been no consensus on the origin. For example, the fluids may be present locally but is unlikely to exist pervasively throughout the deep crust. Magmatic underplating is expected to occur in the lower crust beneath rifts (e.g., the North Sea), extensional terrains (e.g., the USA Basin and Range) and volcanic margins (e.g., the northern Izu-Ogasawara island arc system of Japan) and hence could not be invoked as an explanation for reflective deep crust of fold belts.

Partly because most of interpreters lack dual expertise in both seismology and structural geology, migrated reflection time sections are often converted directly to structural depth profiles and the inherent limitations of seismic reflection techniques in structurally complex areas are frequently ignored. Using perhaps as much art as science and an educated guess, geologists often interpret subhorizontal, discontinuous reflections as elongated high impendence bodies scattered within the crust and/or laminated structures. However, at least two major problems are immediately encountered with this interpretation. First, geologically it is difficult to attribute subhorizontal, discontinuous reflections in the collision-orogenic belts to the origin since lamination usually implies an intensively extensional environment (e.g., Rey, 1993). Second, complex geological structures may not be correctly imaged by conventional seismic reflection (e.g., the Kirchhoff time migration) arising from wave scattering, lateral variations in velocity, interference, limitation of the experimental geometry (i.e., the length of seismic line) and effects of out-of-plane seismic energy on reflections (Drummond et al., 2004). The resultant seismic images of complex folds can be misleading, particularly at great depth. Accordingly, apparent seismic lamellae may not necessarily imply true laminated structures. Can similar reflection patterns be produced by geological structures with a radically different organization?

Folds or fold systems are probably the most remarkable structures in the crust of mountain belts because a great deal of tectonic shortening is absorbed by the folding of rock layers. Folds occur at all scales, ranging from those visible only under a microscope to those extending for tens of kilometres in the crustal rocks. Folds occur in a variety of geological circumstances from near surface sedimentary rocks to lower crust amphibolite- and granulite-facies metamorphic rocks (Griffin, 1974; Sandiford, 1989; Tobisch and Glover, 1971) and deeply subducted ultrahigh pressure (UHP) eclogites (Xu et al., 2004; Foreman et al., 2006), and form under a wide range of tectonic conditions from simple shear to pure shear. A good example of plurikilometre-scale folding in UHP eclogites and coesite-bearing felsic gneisses is found in the area of the Chinese Continental Scientific Drilling

(CCSD) site, Maobei, Donghai County, Jiangsu Province, China (Xu et al., 2004). The eclogites form a set of overturned folds with SE-dipping axial plans. However, no folds occur in high-resolution seismic reflection profiles (Yang, 2002; Yang et al., 2004) although the folds are a prominent feature as observed both on the geological map built based on the surface exposure and in the 5100 m-deep drill cores (Xu et al., 2004).

Folds occur in a great variety of shapes, ranging from very broad and gentle folds to tightly compressed and attenuated structures. Across an orogenic belt, folds occur frequently in extensive fold trains of different sizes and different styles. In the foreland fold belt of the Appalachians, for instance, folds become simpler, less asymmetric, less intense, less tight, less overturning, and have longer wavelengths toward the northwest. Furthermore, folds and faults often occur together in orogenic belts. The foreland margin of a major orogenic belt (e.g., the Appalachian and Rocky mountains) generally consists of a set of asymmetric folds and thrust faults, more or less parallel, that extends for tens or hundreds of kilometres. The asymmetric folds are inclined or overturned toward the same direction as the thrust faults dip. Sometime it is difficult to tell if the thrust faults form by the shearing out of overturned limbs of the asymmetric folds or if the folds develop to accommodate further propagation of the thrust faults. But why are fascinating folded structures hardly seen in seismic profiles of the continental crust? Folds should be considered in the interpretation of deep seismic profiles in terms of tectonic deformation, and detailed studies on seismic reflection characteristics of folds should provide enormous new insight into crustal deformation, structures and evolution.

The results of 2D reflection modeling suggest that multi-order folds, close and tighten folds, inclined folds and overturned folds cannot be correctly imaged by conventional reflection techniques (e.g., the prestack Kirchhoff time migration). The reflections from fold limbs tend to be muted, leaving the crests and troughs that merge laterally into pseudo-horizontal reflections. Because there is no resemblance to folds, these reflections are easily misinterpreted as subhorizontal compositional layering or lamination. Thus, continuous but multi-order folded layer boundaries offer an alternative explanation for the subhorizontal, discontinuous reflections in the deep crust.

It should be kept in mind that any time or depth migration method requires an accurate velocity-depth function, i.e. to specify the value of velocity at each depth. In the case of sedimentary basins, the velocity structure with depth can be determined from analysis of stratigraphic sequences together with information from down-plunge projection and borehole logs where available. In the deep crust of folded orogenic belts, however, velocity is unknowable with current technology and has to be estimated from the seismic data themselves. As there are strong spatial velocity variations in the deep crust, velocity analyses have considerable uncertainty that make them unreliable for migration (Warner, 1987). The construction of an accurate velocity-depth function is such a tricky business that the migration using standard methods often gives unsatisfactory results. Many published time or depth migrated profiles simply employed a constant velocity for the whole crust or lower crust. This could lead to either over- or under-migration. Hence there is always uncertainty if migration has repositioned reflection events to their correct locations on the crustal-scale seismic sections because we have little or no geological control for the deep crust and objective criteria to justify the migration are still lacking. The same time-section can yield very different depth-sections when migrated with different tentative velocities (Damotte, 1993).

Complicatedly folded layer boundaries deflect the transmitted raypaths in all sorts of directions. In 2D seismic surveys as many deep seismic reflection studies do, however, the shot sources and receivers are lined up spatially on such a single straight line that all reflections whose origins are out of the vertical plane containing the seismic line cannot be recorded. As the old saying goes, ‘if you don’t record it, you can’t migrate it’. Thus, 2D seismic reflection profiling offers a spatially filtered version of reality. Furthermore, the lateral resolution of seismic reflections (i.e. the radius of the first Fresnel zone) could be as large as a few kilometres in width at depths of the deep crust, which places limits on the dimensions of folded structures that can be imaged by seismic reflections. In addition, seismic lines are generally crooked and frequently oblique to the strike of geological structures (e.g., Bouzidi et al., 2002). As a result, dipping reflection events identified on the seismic section hardly ever show the true dip of the real structures and thus the obtained seismic image would be severely biased (e.g., Calvert, 2004). For all the above reasons, information about fold geometry can hardly be acquired from deep seismic profiles. Thus, reflections due to complex multi-order folds from many deformed crystalline crust may have been overlooked or misinterpreted.

Disharmonic folds are characterized by a substantial change in fold shape between adjacent layers and a general decoupling of folded layers through the stratigraphic sequence. These folds are formed by the folding of stronger layers (e.g., amphibolite) in much more ductile matrix (e.g., mica schist or felsic metavolcanites). The weak layers change thickness appreciably as they undergo strongly plastic flow from the limbs to the hinge zone, whereas the strong layers undergo flexural folding and even brittle fracturing and change little in thickness. Such folds also occur in moderate to high-grade metamorphic rocks and may prevail in the middle and lower crust. As there is a positive correlation between rheological properties and seismic velocities (Passchier, 1986; Pfiffner et al., 1991; Ji et al., 2002) at a given depth or temperature, the rheologically stronger layers have generally higher seismic velocities. It is thus strongly possible that disharmonic folds may cause interfingering or ‘crocodile’ patterns (e.g., Meissner et al., 1991) in seismic reflectivity images.

Superposed folds are common features in metamorphic terrains of shield areas and in the infrastructure of young orogenic belts. Fine examples of large-scale superposed folds are those mapped in the Charlotte belt (Tobisch and Glover, 1971) and the Inner Piedmont belt (Griffin, 1974) of the southern Appalachian orogen (Virginia, North Carolina, and South Carolina, USA), where gneises, schists and amphibolites are exposed at the surface. Such folds result from successive folding and refolding of the rock layers during the ongoing progressive deformation of a single orogeny or during successive unrelated deformation events, widely separated in time, and associated with the superposed orogenic belts or discrete orogenies within a single belt. These multi-phase fold systems could cause complex reflectivity patterns. Moreover, large-scale, asymmetric, recumbent, chevron or kink folds (e.g., Suppe, 1985) may produce seismic wedges and duplexes (e.g., Cook et al., 1999).

In the continental crust, shape, symmetry and style of folds vary with tectonic environments and reflect both physical conditions (e.g., T, P, strain, strain rate, state and magnitude of stress) and the mechanical properties of rocks when the folds developed. If we can calibrate the relationship between seismic reflection features and fold geometry, we may develop a valuable method to constrain in-situ structures and deformation in the crust using seismic reflection techniques.

An example is given in the following. Fig. 6a is a seismic reflection profile across a continent-continent collision belt between the Archean Sask and Superior cratons during the Hudsonian orogeny with an age of 1.88−1.72 Ga (White et al., 1999). The seismic profile, which extends from the Kisseynew Belt across the Superior Boundary Fault into the Superior Boundary Zone, was acquired by Lithoprobe in 1991 in northern Manitoba, Canada. Fig. 6b is a high-resolution image from the shallow crust (<6 km) of the Superior Boundary Zone. The comparison of the image with structural synthesis of the surface geology (Bleeker, 1990) suggests that the horizontal and slightly arcuate reflections (Q) within the Superior Boundary Zone that extends to about 6 km are most likely due to complex folding of layered rocks. The moderate east-dipping reflections (R) can be attributed to either shear zones or trains of asymmetrical folds. These asymmetrical folds indicate an east-side-up ductile shear, consistent with the surface geology.

As shown in Fig. 6a, the middle crust of the Superior Boundary Zone, from ∼12 km depth to 30 km depth, is characterized by a predominance of west dipping bands of reflections (K). As the boundary zone between the Superior Craton and the Reindeer Zone was a Superior-verging thrust belt during the orogeny, the seismic reflections can be produced by Superior-verging asymmetrical folds and/or thrusting shear zones with contrasted lithologic layers. In the lower crust, there are discontinuous subhorizontal reflections. According to White et al. (1999), the Moho occurs at approximately 15 s, indicating a crustal thickness of about 49.5 km using an average crustal velocity of 6.6 km/s. The discontinuous subhorizontal reflections are most possibly originated from the multiple-ordered folds with complex geometry.

5. Conclusions

This paper emphasizes the failure of conventional seismic reflection techniques (e.g., prestack Kirchhoff time migration method) in imaging complex geological structures such as folds. The failure stems from the inherent inability of the techniques to account for lateral variations in velocity and to display steeply dipping reflectors. The techniques have a selective vision of gently dipping or horizontal reflectors in the deep crust. The inherent limitations are well known but unfortunately are often ignored in the geological interpretation of seismic reflection profiles. In order to show the dangers in blind interpretation of seismic profiles, Kirchhoff-type forward modeling has been performed on various types of fold trains including single-order open folds, close folds and asymmetric inclined folds as well as multi-order folds. The synthetic sections show that the reflections from steeply dipping fold limbs tend to be muted, leaving the horizontal crests and troughs that merge laterally into

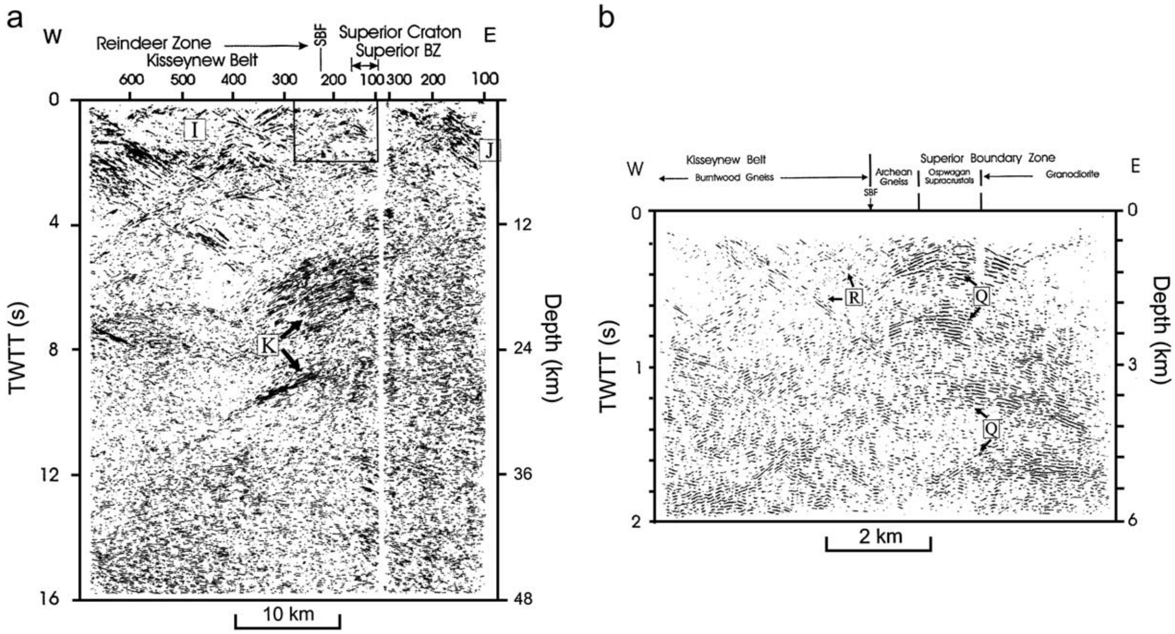

Fig. 6. Merged seismic reflection images for the collision belt between the Sask and Superior cratons in northern Manitoba, Canada. The rectangle in (a) indicate location of the corresponding high-resolution data shown in (b). Labels are referred to in the text. SBF is the Superior Boundary Fault, and BZ is boundary zone.

pseudo-horizontal reflections. The reflection images bear no resemblance to folds but mislead, instead, the presence of subhorizontal reflections. The latter is often interpreted as subhorizontal layering or compositional lamination formed by crustal extension or underplating. It is clear that that the compositional lamination is not necessarily the sole source of subhorizontal reflections. Complex folded structures due to intensive shortening may also produce such subhorizontal reflections, but the latter are generally more discontinuous laterally and less dense than those caused by simple lamination. Interestingly, the reflections observed in cratons and fold belts are generally laterally shorter and less dense (except in ductile shear zones) than those observed in the extensional regions. This indicates that seismic lamination may correspond to laminated lower crust in extensional regions such as the Basin and Range (USA), but most likely to complex folded structures beneath both ancient and modern fold belts.

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