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State-of-the-Art of the Phanerozoic Isotopic-Geochronologic Scale

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Abstract—The modern substantiation of the boundaries in the Phanerozoic scale of geologic time is discussed with reference to absolute geochronology. The critical analysis of the isotopic–geochronologic data that form the basis of modern scales shows that only a few of them are suitable for calibration of an adequate scale. At present, reliable dating is available for the following boundaries: the Cambrian lower boundary (535 Ma); the Ordovician–Silurian (440 Ma); the Jurassic–Cretaceous (more than 137 Ma); the Cretaceous–Paleogene (65 Ma); and the Paleogene–Neogene (23 Ma). Moreover, the available data allow determination of many age boundaries in the Ordovician, Late Cretaceous, Paleogene, and Neogene and evaluation of boundary ages between several epochs: the Early–Late Silurian (421 Ma); the Middle–Late Devonian (367 Ma); the Early–Middle Triassic (238 Ma); and the Early–Middle Jurassic (less than 185 Ma). The principles of calibrating the modern scale, in particular the priority of the "geochronologic" approach, are discussed, as also the prospects of future work on the scale and the necessity to elaborate the geologic time scale in this country.

Key words: *isotopic geochronology, chronostratigraphy, geologic time scale, volcanites, the Phanerozoic.*

There is no need to justify the primary importance of an adequate Phanerozoic scale of geologic time for unequivocal correlation between the relative (chronostratigraphic) and the absolute (isotopic) ages of Phanerozoic geologic objects and processes. It should be noted, however, that the quality of the applied scale affects the correctness of the reconstruction of the Phanerozoic history of geologic evolution of separate regions and of the Earth as a whole. Moreover, the correct scale helps to find in this history a place for unstratified (intrusive, ore etc.) bodies, to time the absolute chronology of the main stages in biosphere evolution, to prove the synchronism of sedimentary and magmatic rocks, to afford correct interregional correlations, and to substantiate the serial legends to geological maps. It is also obvious that the adherence to absolute chronology is one of the few tools, if not the only one, for correct correlation of the local and regional stratigraphic scales with the Global Stratigraphic Scale (GSS), when the necessary and sufficient paleontological data are lacking.

The urgency of this problem explains why scientists abroad are persistently searching for perfection of the geochronologic scale in terms of absolute chronology. Despite new data and constant improvement of dating methods, however, none of the existing scales is satisfactory from the point of view of the modern methodology of isotopic–geochronologic research. The present paper is dedicated to the analysis of the current state of the problem and to the ways of its solution.

A few considerations are appropriate before passing to the main part. First, I will not discuss here the scales based on the supposed effect on the Earth's geologic history of its position in the Galactic orbit, which thus correlates the periodicity of geologic events with the time of the Galactic year (Yasamanov, 1993; and others). As I believe, these suppositions are speculative and still insufficiently substantiated, if only due to the ambiguity of the magnitude of the Galactic year. Furthermore, the understanding of this periodicity is based on the existing "normal" scales, the validity of which is far from perfect. Second, I am not a specialist in paleontology and stratigraphy and, therefore, refer the problems of the stratigraphic basis of the geologic time scale (if it is available) to the proper professionals. Third, only the state of the pre-Quaternary Phanerozoic scale is discussed in this paper. The Quaternary formations are dated mainly by applying specific methods that require special discussions by experts. And finally, one remark on terminology. I use the term "geologic time scale" instead of the term "geochronometric scale," recommended in the last issue of the Stratigraphic Code (*Stratigraficheskii* ..., 1992, p. 22) for the "geochronologic scale", the boundaries of which are determined in absolute units. I think it is more natural to call this scale "geochronologic" and to designate the scale implied by the Stratigraphic Code as "chronostratigraphic" or "geohistoric." I am, therefore, using the definition Phanerozoic geologic time scale, PGTS, in this paper to avoid the unsatisfactory term "geochronometric" and the ambiguous "geochronologic." This concept is extensively applied in foreign scientific literature, where it naturally combines two types of scales, the chronostratigraphic and the chronometric (Harland *et al.*, 1982).

THE PRINCIPLES OF APPLICATION OF ISOTOPE GEOCHRONOLOGY IN PGTS CALIBRATION

It is apparent that in calibrating an adequate geologic time scale, we should follow certain rules, the most important of which are as follows: (1) the object selected as a bench mark (reference point) should be exactly correlated with the GSS; (2) the isotopic age of the object should be determined with required precision and unequivocally proved; (3) the isotopic age should correspond rigorously to the geologic age. Leaving the problem of chronostratigraphic allocation out of this discussion, let us review the possibilities of isotopic dating in precise age determination of objects used to compile the PGTS. Otherwise its current state would be difficult to assess.

The limitations of one paper do not allow the elucidation of all problems of acquisition and interpretation of the isotopic–geochronologic data, which has been treated in numerous publications in this country and abroad. Therefore, I present a brief review of the possible system of evidences proving the reality of measured ages, provided that the results of research without adequate proof are to be ruled out for the construction of the scale, although in certain cases they can be employed as "restricting" factors, or for other applied purposes.

The essence of independent isotopic proofs applied to justifying correctness of radiological age determinations is based on a reliably established difference in the geochemical behavior of almost all isotopic–geochronometric systems in natural processes. The systems imply a concrete pair of parent–daughter isotopes in a certain natural geochronometer, e.g., the Rb–Sr system of biotite, or the Sm–Nd system of the whole rock. This means that in the absence of distorting factors, all methods applied in isotope geochronology for the whole rock (bulk samples), or its mineral components, will determine identical time corresponding to the age of the object. In practice, the reverse statement is also true: the coincidence of measured ages for all isotopic–geochronometric systems implies the absence or insufficient intensity of distorting factors, and definitely proves the correctness of the age obtained for the object being studied.

The global experience of geochronology shows that obtaining the necessary proofs does not require the use of all the methods for all rocks and minerals composing the object being studied. In most cases, it is enough to apply two or three methods to a restricted number of natural geochronometers; in favorable conditions, one method will suffice to obtain the necessary proofs. To achieve that, the methodologically correct application of each method is necessary in order to use criteria of authenticity that are inherent to any of them and based on the regularities of geochemical behaviors of isotopes in corresponding systems. Further elucidation of these problems can be obtained from special publications (Pushkarev *et al.*, 1978; Shanin *et al.*, 1979; Rublev, 1984; and others). Avoiding a number of methodological problems and proofs, I shall briefly formulate these criteria as applied to each method.

In the U–Pb method, when zircon is the most frequently used mineral for geochronological research, the basic criterion of authenticity is the coincidence of the measured ages calculated by three isotope ratios: $^{206}Pb/^{238}U$, $^{207}Pb/^{235}U$, and $^{207}Pb/^{206}Pb$, i.e., the internal concordance. If the zircon data are discordant, then a series of samples of one generation is used to plot the discordia on the Ahrens–Weserill coordinates. The upper intersection of the isochron with the concordia shows the time of formation of the studied zircon generation. The greatest disadvantage in the U–Pb method is the presence of xenogenic components in zircons, and then they are discordant. The formation time of these zircons is determined by the lower intersection of discordia with concordia if the former can be derived. Consequently, a single dating by one ratio cannot be regarded as reliable without an analysis of all analytical data. To a still higher degree, the data of the alpha-lead and fission-track methods used earlier cannot be applied here.

The Rb–Sr and Sm–Nd methods are used for separate minerals and for rocks, in the latter case, invariably in the isochron variant. The necessary condition for correct results is the correspondence of the studied series of samples to the isochron model, which is determined by the value of the mean square weighted deviation (MSWD) of the order of a unit. The criterion of reliability is the obligatory coincidence of ages of different minerals with the isochron age, i.e., the distribution of data points corresponding to the minerals on the isochron for the whole rock sample. In certain cases, the coincidence of the measured ages of different minerals is sufficient, and the rock samples may not be involved. Any single dating by minerals, the monomineral isochrons, or isochrons by the whole rock samples cannot be regarded as reliable, if the age is determined only from these results. This statement does not mean that the isochrons are necessarily misrepresenting, however, in such cases they lack reliable proof that the system has never been disturbed.

When the K–Ar method is applied, the main criterion of data reliability is the coincidence of the measured ages of different minerals from the rock sample, which are clearly different in their ability to lose the radiogenic argon. At mild discordance, if the measured ages correspond to a series of minerals variably resistant to the loss of argon (in declining order: amphibole

/pyroxene/—muskovite—biotite—feldspar—glauconite), then an analysis of minerals from a series of samples is required to find regularities in the variation of differences in age measurements and to reveal the minerals, the K–Ar system of which remained intact under external effect. The greatest risk (albeit rare) in K–Ar dating, but is the excess, of argon of various origin in almost all minerals except muskovite. Therefore, the analysis of whole rock samples only, or minerals with low stability to the argon loss (feldspars, glauconites), can produce at best only information about the upper age limit of the formation time of the object.

Authors abroad often use data from the age spectra method ($^{40}Ar/^{39}Ar$). We should be careful in trusting these data, because they can be assumed as undistorted only if the plateau ages of different minerals coincide. In this case, the plateau itself should correspond to 70–90% of the extracted argon in total. This remark does not concern biotites, which can display the plateau regardless of the loss or capture of argon.

If in the course of geochronologic study a certain method fails to produce the required proofs of the actuality of the measured age, it is necessary to apply at least one other method according to the mineral–geochemical peculiarities of the object being studied. Moreover, since we do not know *a priori* the number and intensity of natural factors distorting the isotopic systems, it is necessary to employ at least two isotopic-geochronologic methods for dating the reference objects.

Now I consider the possibilities for reliable age determination of different rock types generally used to compile the current PGTS also in view of the geologic significance of the isotope age.

Intrusive rocks, except ultrabasic, are preferable for isotope datings, because they can be treated by all isotopic–geochronologic methods, and the maximal number of natural geochronometers can be applied to them. As shown by the world geochronologic experience, the methodologically correct isotopic methods of study of petrographically unaltered Phanerozoic intrusive rocks produce reliable datings in the absolute majority of cases. It is considerably more difficult to determine the age of intrusions greatly altered by secondary processes and rocks of complicated genesis lacking the stage of isotope homogenization in the magmatic melt.

Though the intrusive rocks are preferable for isotopic dating, they are hardly suitable as markers for the scale. The intrusive rocks seldom have accurate enough chronostratigraphic allocation. In most cases, we are able to determine only their upper or lower age boundary, and the age interval between the moment of intrusion emplacement and one of these boundaries is often too long (no less than several million years) to pose the boundary in the scale. Furthermore, the geologic age of intrusions corresponds to the time of magma intrusion, whereas the isotopic chronometers fix a certain moment in rock evolution, when magma has already crystallized and the temperature has dropped to the level, at which the corresponding isotopic–geochronologic systems close up. There is evidence that the indicated interval in the life of meso- and hypabyssal intrusive bodies can be no more than a few million years (Rublev, 1986), but the summary effect of these two factors make intrusive bodies practically unsuitable for chronostratigraphic markers.

Volcanic rocks can be dated with more difficulties than intrusives owing to two main causes. The first is the low degree of crystallization of volcanic rocks which makes extracting the necessary minerals of requisite quantity and purity difficult. However, with the improvement of the analytical technique, the effect of this factor decreases. The second cause is the frequent alteration of volcanic rock up to complete secondary transformation of the mineral-geochronometers. In such cases the sampling of the necessary rock material is arduous. If it is achieved, then the age determination of the volcanic rocks is almost identical to that of the intrusives, though with certain specific aspects (Bibikova, 1985; Gorokhov, 1985; Morozova *et al*., 1985). Moreover, the K–Ar and Rb–Sr methods are mainly used when dating volcanic rocks, because the application of the U–Pb method is hindered by the difficulty of zircon extraction.

For more precise specification of the geologic time scale, the volcanic rocks as markers are indubitably superior to all other types of rocks according to such properties as geologically “instantaneous” formation, which makes their “isotopic” and “geologic” ages identical. However, volcanic rocks are prone to cause difficulties in rigorous chronostratigraphic allocations. In fact, the most suitable rocks for isotope dating are those of acid and intermediate composition typical of continental environments. Naturally, the stratigraphic allocation of marine volcanites is more precise and reliable, but the majority of them are basaltoids, the most difficult rocks for isotopic dating. Progress in basaltoid age determinations, I believe, can be made with the Sm–Nd method, provided the accuracy of determination of Nd-isotope composition is improved.

Phanerozoic sedimentary rocks, the natural markers for the stratigraphic scale, cannot be reliably dated with modern techniques of isotopic geochronology. Only the minerals of the glauconite group (MGG) and illites or mixed-layer illite–smektites can be used as “geochronometers,” whereas isochron dating of the whole rock samples is pointless for many reasons. The MGG are characterized by a rather low stability against the thermal losses of argon that can become actually perceptible above 50°C with due regard to the real duration of geologic processes (Aprub and Levskii, 1976); i.e., already at the depths of about 2–3 km. Besides, unlike other minerals, except biotites, the MGG have nearly identical stability of K–Ar and Rb–Sr systems, which precludes the application of such reliability criterion as coincidence of ages obtained with different methods.

Therefore, an age value obtained for glauconite, even if this mineral is perfect by all mineralogical and geochemical parameters (Odin, 1982a), is valid for application only as the upper age limit for that rock. Strictly speaking, even this is not always true, because several researchers suggest the possible inclusion of redeposited older glauconite in sedimentary rocks.

Illites as geochronometers are, no doubt, more reliable. According to the published data, their K–Ar and Rb–Sr systems have different stability against external impacts and, therefore, the coincidence of K–Ar and Rb–Sr ages for illites from unmetamorphosed sedimentary rocks is, apparently, the most precise determination of their time of formation, provided they are represented by one generation. The latter hardly ever occurs. Most frequently, the illite in sedimentary rocks is a mixture of two or three generations, and their separation into pure monogenetic components is extremely complicated and laborious (Gorokhov *et al.*, 1994). The main drawback of illite as a sedimentary geochronometer, however, is that it is formed not during deposition, but in the course of diagenesis of sediments and (or) their epigenetic transformation. This means that without the determination of the time interval between the indicated processes, which is hardly the same in different geologic situations, the dating of illites can likewise be used only as the upper age limit of the host rock. This is also true, to a certain extent, of the MGG, though there are data about their possible formation at the early stages of sediment lithification.

The improvement of analytical procedures enables an increasing amount of data on bentonites and volcanic ashes to be used for PGTS elaboration. On the one hand, these rocks contain materials from volcanic eruptions, including minerals traditionally used for isotopic dating (biotite, sanidine, zircon). On the other hand, these rocks can often be fixed with precision to the GSS. The main difficulties in handling these rocks are the small amounts of the necessary minerals, their alteration and possible xenogenic contamination (Baadsgaard and Lerbekmo, 1982). If these obstacles are overcome, then the dating of bentonites and volcanic ashes differs from the datings of magmatic rocks only by the impossibility of using isochron methods for the whole rock, which is, by the way, not always necessary.

THE PRESENT STATE OF GEOCHRONOLOGIC SUBSTANTIATION OF THE EXISTING PGTS

Proceeding from the above, I would emphasize two aspects that should be taken into account when estimating the validity of any scale. (1) For different reasons, the intrusive and sedimentary rocks (except bentonites and volcanic ashes) should not be used at present for the construction of an adequate PGTS. The results on these rocks, even with correct application of the isotopic–geochronologic methods, can determine only the age restrictions (most often the upper age limit) for the scale unit boundaries. (2) The determinations cannot be regarded as reliable if they are made, irrespective of the method, only for the whole rock samples; for glauconites and biotites with K–Ar and (or) Rb–Sr methods; for any individual mineral, except zircon, with one method; or by $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ ratios, if they are the only substantiation of the age.

With this in mind, let us discuss the isotopic–geochronologic data now used in the calibration of the most popular PGTS. We will begin with the analysis of the data for the scale of the London Geological Society (Harland *et al.*, 1964), because many of them were incorporated into all other later scales. Its calibration was based on the dating results of 337 objects traditionally designated in scientific literature as PTS 1–337. They were later amplified by data for 29 other objects designated as PTSS 338–366 (Harland *et al.*, 1971). If we exclude from these data those, to which the restrictions mentioned above are applicable, and those obtained from altered samples and rejected by the authors of the scale due to the inaccuracy of chronostratigraphic allocation, then the results on only 15 objects will remain suitable for the PGTS construction. Three of these objects belong to the Miocene (PTS 262–264; 266–269, and 275), one to the Eocene–Oligocene boundary (PTS 300), one to the Paleocene (PTSS 362), one to the Cretaceous–Paleogene boundary (PTS 199), and six objects to the Late Cretaceous (PTS 201, 202, 204 and PTSS 363, 364, 365). One more object belongs to the Devonian (PTSS 354), and two others to the Ordovician (PTS 156, 157). Therefore, these data are obviously insufficient for compilation of a proper scale.

In 1982, Harland and his co-authors, recognizing the weak points of the scale, the availability of new data, and the need to recalculate numerical values of boundaries in accordance with new constant rates of radioactive decay (Steiger and Jager, 1977), suggested a new variant of the PGTS (Harland *et al.*, 1982), which nonetheless preserves the bulk of the results for the scale of 1964. When R.L. Armstrong discredited several datings with the addition of his own data, presented at the symposium on the scale at the 25th International Geological Congress, and when other results on new objects were reported by other participants (Cohee *et al.*, 1978), the isotopic–geochronological basis of the new scale was not appreciably improved, because most of the materials of the Sydney Symposium do not meet all aforementioned restrictions.

As a result of work on the International Geological Correlation Program (Project 133), G.S. Odin published, also in 1982, another well-known variant of the PGTS (Odin, 1982b). It was based on age determinations of 251 objects. Since the data were presented in the monograph: *Numerical Dating in Stratigraphy* (1982), their traditional abbreviation is NDS. In this case, the age determinations were obtained for 135 glauconites, 24 whole rock samples were dated by the K–Ar method, 21 by the Rb–Sr method, etc. As a result, only seven objects can be considered to be reliably dated; three of them belong to the Cretaceous (NDS 105, 111, 127), two to the Early Jurassic (NDS 183, 184), one to the Ordovician (NDS 129 = PTS 156), and one to the Early Miocene (NDS 155). With certain restrictions, the data are usable for seven other objects (NDS 103, 104, 106, 107, 118, 157, 218). All of them were obtained by the K–Ar method from unaltered biotites in bentonites and correspond to the Late Cretaceous. As shown in practice, these datings are seldom distorted, but even their application insufficiently substantiates the suggested scale.

The principal difference between the two scales of 1982 is in the age determination of the Cambrian lower boundary. Odin estimated it to be 530 Ma old, while Harland and co-authors suggested the level of 590 Ma. The data for the Cretaceous lower boundary differed by 14 Ma (130 and 144 Ma, respectively), and by 20 Ma (418 and 438 Ma) for the Silurian lower boundary. Other disparities are not substantial, but for reasons discussed above this does not imply that the accepted age values are correct.

In 1982, at the Seminar *"Geochronology and Geological Record"* in London, a comprehensive discussion of the PGTS focused on several problems: the high diversity of available scales, the discrepancy in the principles of their calibration, new results including those obtained at an updated level of research on former objects, and improvement of the stratigraphic basis. Proceedings of the seminar were published later (*The Chronology* ..., 1985), and from their data and discussion results Snelling (1985) suggested another well-accepted PGTS variant, actually the compilation of the 1982 scales. Few of the new result, debated at the seminar, merit consideration, primarily those on the Late Devonian (Frasnian) volcanites of the Cerberean Caulderon Formation 367 Ma old (Williams *et al.*, 1982) (NDS 234) and the Ludlovian volcanites of the Laidlow Formation 421 Ma old (Wyborn *et al.*, 1982). The absolute majority of other data was either on intrusive rocks, or unreliable.

The American scale of 1983 (Palmer, 1983), frequently mentioned in the literature, is a pure compilation of the 1982 scales mentioned above and the data of the London seminar. Essentially the same is the latest scale by Harland and co-authors (Harland *et al.*, 1990). It will suffice to mention that among 670 isotopic ages for the Phanerozoic part of the scale, 163 are derived from the first work of the authors (Harland *et al.*, 1964) and 278 from the scale of 1982 by Odin.

The situation with reference dating of objects with stratigraphically reliable allocations has been improving lately owing to a more extensive application of bentonites and volcanic ashes as indicators. A typical example is the studies carried out during many years by H. Baadsgaard, J. Lerbekmo and their co-authors of the Cretaceous–Paleogene (65 Ma) and Campanian–Maastrichtian (73 Ma) boundaries. The research was accomplished with combined isotope–geochronological methods of study on bentonites in Canada (Badsgaard *et al.*, 1988, 1993).

No less impressive are the results obtained with the U–Pb method on zircons from the interbeds of volcanic ashes in the Ordovician and Lower Silurian stratotypes of Britain. The sufficiently concordant age values in all isotopic aspects allowed the highly reliable determination of the Ordovician–Silurian boundary age at about 440 Ma and that of the Llanvirnian and Llandeilian ages at 464 Ma (Tucker *et al.*, 1990).

Equally reliable geochronologically, but less definite chronostratigraphically, the data for the Ordovician rhyolites from the Buchans and Robert Arm formations in Canada suggest that the lower boundary of the Llanvirnian Stage is 473 Ma old (Dunning *et al.*, 1987; Dunning and Krogh, 1991).

Very important and geochronologically reliable results were obtained for zircons from the Lower Cambrian ashy tuffs in the lower reaches of the Lena River (Bowring *et al.*, 1993). According to this data, the lower boundary of the Cambrian, which Russian geologists place at the base of the Tommotian Stage, is 535 Ma. The Resolutions of the International Stratigraphic Commission state that the lower boundary of the Cambrian lies at the base of the *Phycodes pedum* Zone (Landing, 1994) and, therefore, the lowermost Cambrian should include the pre-Tommotian Nemakit–Daldyn Stage. In this case, the age of the Cambrian–Precambrian boundary is 545 Ma. In any event, the age of the Cambrian lower boundary should be much younger than 560–570 Ma as was generally assumed.

As confirmation of the results on NDS 183 and 184 for the Pliensbachian–Toarcian (Early Jurasic) subvolcanic rocks of the northern Caucasus, a quite reliable age value in the 180–190 Ma interval was obtained by the $^{40}Ar/^{39}Ar$ method for biotites and plagioclases (Hess *et al.*, 1987).

The sufficiently adequate U–Pb dating of zircons from the tuff interbeds in California imply that the Jurassic–Cretaceous boundary is somewhat older than 137 Ma, whereas the Berriasian–Valanginian boundary is about 135 Ma old (Bralower *et al.*, 1990).

Many publications have been recently dedicated to the different methods of age determination of the Eocene–Oligocene boundary by using the products of volcanic eruptions in northern Italy, and the generalized results indicate that it corresponds to the 33–37 Ma interval (Odin *et al.*, 1991).

All these results were incorporated by Odin in the recently published PGTS (Odin, 1994). But the new variant differs only slightly from the 1982 scale, that is acknowledged by the author. And no wonder, since the new scale retains the earlier data on 251 objects from the 1982 scale, and the larger part of the 150 new age determinations does not comply with the necessary requirements. This observation also refers to such seemingly reliable data as those cited in the works by

Claoue-Long and co-authors on age determination of the Permian–Triassic (251.2 ± 3.4 Ma) and Devonian–Carboniferous (353.4 ± 4.0 Ma) boundaries with the U–Pb method on zircons from bentonites (Claoue-Long *et al*., 1991, 1992). Two circumstances, caused by the fact that the analytical results were obtained with the ion mass spectrometer SRIMP, prevent the acceptance of the results for the reference points of the scale.

First, though the application of the SRIMP technique implies a large number of individual determinations, their values are obtained with considerable defects. The authors carried out a specific mathematical processing of the results, which though reduced the final error, but still produced a real error value at least 5–10 times greater than the indicated one. Second, the most serious errors in this technique are associated with the measurements of $^{207}Pb/^{235}U$ ratio, and precludes the accurate determination of the position of data points on the diagram with concordia, in other words, the evaluation of possible losses of radiogenic lead or the presence of xenogenic component. The authors, practically *a priori*, have to assume the absence of such phenomena, and this likewise discredits the presented results as scale markers. By the way, insufficient accuracy also prevents acceptance of the age determination of the Permian–Triassic boundary at 249 ± 15 (1σ) Ma obtained by Rb–Sr method on whole rock samples and minerals from basalts of the Polar Urals (Andreichev, 1992).

The latest materials on the PGTS known to the author were presented at the Eighth International Conference on Geochronology, Cosmochronology and Isotope Geology in June 1994 in Berkeley. The major part of the materials, satisfying the requirements of scale construction, were on the Neogene and Paleogene (Montanari and Swisher, 1994; Montanari *et al.*, 1994; Deino *et al.*, 1994). The results were obtained mainly by using different modifications of K–Ar age determination of volcanic rocks and ashes from the Cenozoic sections in Italy. They permit the establishment of reliable age boundaries for several epochs and ages of the indicated periods. Interesting results were also presented on the age determination of the lower boundary of the Middle Triassic by U–Pb method applied to zircon grains from the interbeds of volcanic tuffs in the southern Alps (Mundil *et al*., 1994). Though the paper presents the age values calculated only by $^{206}Pb/^{238}U$ ratio, they allow the reliable age of the boundary to be no less than 238 Ma when combined with $^{40}Ar/^{39}Ar$ data on feldspars for NDS 196.

Consequently, if the stratigraphic position of the enumerated objects is correct, then the isotopic–geochronologic justification of PGTS at the beginning of the second half of 1994 is as follows. The Tommotian Age starts at 535 Ma (Bowring *et al.*, 1993), or even earlier (Isachsen *et al.*, 1994), but there are no reliable data on the Ordovician stages before the Llanvirnian. Apparently, the age of the Llanvirnian lower boundary is quite different from 473 Ma (Dunning *et al*., 1987; Dunning and Krogh, 1991). The Llanvirnian–Llandeilian boundary is 464 Ma old, whereas the boundary ages of the following Ordovician stages can be identified by interpolation in a rather short age interval. The age of the Ordovician–Silurian boundary slightly differs from 440 Ma (Tucker *et al.*, 1990) as it follows from data for NDS 129, PTS 156, and PTS 157. The base of the Ludlovian (Early–Late Silurian boundary) is somewhat older than 421 Ma (Wyborn *et al.*, 1982), but from there until the early Frasnian, or 367 Ma (Williams *et al*., 1982), reliable age determinations are lacking. The Devonian–Carbonineferous, Carboniferous–Permian, Permian–Triassic, and Triassic–Jurassic boundaries are inexactly dated. Only some intervals can be suggested on the basis of age determinations of intrusions protruding them. The age of the Early–Middle Triassic boundary is also estimated to be 238 Ma (NDS 196) with sufficient reliability (Mundil *et al.*, 1994). In the Lower Jurassic, near the Pliensbachian–Toarcian boundary, two marker objects (NDS 183, 184) are dated as about 185 Ma old, but with a serious analytical error of no less than 10 Ma. A similar dating of this boundary is confirmed by the data in the paper by Hess *et al.* (1987). The next marker, the Berriasian bentonites, is 137 Ma old (Bralower *et al*., 1990), and further until the Early–Late Cretaceous boundary there are no reliable age determinations of stratigraphically well-allocated objects.

The remaining part of the scale, from the beginning of the Late Cretaceous to the Quaternary, can now be considered justified even up to the boundary ages of almost all the stages. At least, the few discrepancies between different sources do not exceed 1–3 Ma, and that owing to analytical errors or inaccuracy in stratigraphic allocations. To sum up the results on this part of the scale, I would note only the boundary ages between epochs; i.e., between Early and Late Cretaceous (97 Ma), Late Cretaceous and Paleocene (65 Ma), Paleocene and Eocene (53 Ma), Eocene and Oligocene (34 Ma), Oligocene and Miocene (23 Ma), Miocene and Pliocene (5.3 Ma). More details can be derived on this part of the scale from a paper by Odin (1994). The age of the Quaternary lower boundary requires a more precise definition within the interval of 1.5–2.5 Ma.

The results presented above represent the entire data set derived from available publications. No doubt, part of the data, particularly the most recent, is probably omitted due to restricted access to foreign publications nowadays. But the missing information can hardly make essential changes in the represented situation. Obviously, the adequate PGTS is at present fragmentary and requires further study. In this context, I discuss certain problems and questions below.

DISCUSSION

One of the main problems is the elucidation of the main principles of the PGTS calibration. Odin distinguishes three approaches: statistical, graphic, and geochronological (Odin, 1994). Like Odin, I certainly belong to the supporters of the priority of the geochronologic approach and, therefore, do not present my own variant of the scale in the traditional sense. I completely agree with Odin's comments on the statistical and graphic (interpolation) approaches along with the main points of the mentioned paper, to which I add the following remarks.

The interpolation method for regular division of any time interval between sufficiently remote reference points of the PGTS into a number of basic units (ages or stages, after Odin) of this interval should not be applied because of the different duration of the stages even within one period. If we take the PGTS subdivisions adopted in this country (*Stratigraficheskii* ..., 1992), and the stage durations, which are often approximate and derived from the existing scales, we shall see that there are short stages of 1–5 Ma (Piacenzian, Coniacian, Anisian, Llandeilian) and much longer ones of 10–20 Ma (Campanian, Albian, Visean, etc.). It is, therefore, obvious that the application of the interpolation method (e.g., Harland *et al*., 1982, 1990) can be excused by the lack of a sufficient number of reference points and the necessity to use in practice any PGTS more or less approximating the real one. This method has nothing in common with the proper way to construct an adequate scale. This statement does not mean that the interpolation approach is inapplicable for that purpose in general. It can and should be used, but only for placing the stage boundaries, if we have reliably dated objects in the neighbouring stages, while the boundary age itself is undetermined.

Just one remark about the statistical method: no amount of statistical processing of unreliable age measurements can improve their authenticity. This method reveals the most frequent value, but its reference to the real age can be known only after correct dating of the corresponding boundary. Likewise, there is no point in statistical processing of the age values for unit boundaries accepted in different scales, as done by Afanas'ev (1987, 1993) in his publications. The basic approaches of this author merit special critical analysis. I shall mention here two items.

First, Afanas'ev rejects some boundary values using such criterion as occurrence frequency, but not the rate of geochronological reliability. Consequently, it is apparent that this approach will result in the loss of reliable determinations, because they are in the minority. For example, the lower boundary of the Tommotian Stage was dated as 530 Ma old only in Odin's scale of 1982, while in other scales the pertinent value varies from 560 to 600 Ma. Naturally, Afanas'ev rejected it, although the most realistic value of the boundary today is 535 Ma.

Any statistical processing of a series of values will, of course, result in a more precise average, if the most outstanding figures are rejected. There is yet another aspect of Afanas'ev's approach. His data sorting suggests that boundary ages measured with minimal errors are to be included into the sample. This means that all of Afanas'ev's scales, except the first one, will incorporate all their previous variants with the accuracy of the calculated boundary ages artificially increasing with time. If prolonged, this process may result in zero error in the age determinations of boundaries, but the sample will finally contain only Afanas'ev's own artificial scales. It seems apparent that such values may have only accidental coincidences with the actual age of the unit boundaries.

The criticism of the modern statistical method and interpolation approach does not entirely exclude their application. The former method can be used, if a large number of reference age determinations is available for a certain limited chronostratigraphic interval (less than an age). In this case, the statistical method will either improve the accepted value (if all age values in the sample do not differ within the analytical error), or reveal the inaccuracies in the chronostratigraphic allocation of objects or the "age" slip (provided the range of age determinations considerably exceeds the analytical error). In fact, we still have to wait for a real opportunity to apply the statistical method to most of the boundaries.

The essence of the "geochronological" principle of the PGTS calibration is given in the three items of the first part of the paper, and it must be strictly satisfied, I think, particularly with regard to the isotopic–geochronological data. This rule is important not only for the correct solution of the problem and as a way to avoid ambiguous results. The strict requirements are justified by the greater possibilities of modern isotope geochronology, such as (1) greater precision of age measurements, which in favorable situations approaches 1–2 Ma for the Paleozoic and Mesozoic and less than 1 Ma for the Cenozoic; (2) the greater sensitivity of the isotope analysis that allows the use, in the best laboratories, of extremely small amounts of minerals; (3) current progress in the understanding of how the real, true age of objects could and should be obtained (and proved). Moreover, I think that only the application of precise and reliable ages of stratified formations can help resolve debated problems in stratigraphy, including those related to the PGTS calibration.

The "geochronological" approach to the PGTS calibration prescribes the character of future work with the scale. I believe that there are now two mutually complementary ways of calibrating an adequate scale. The first is to conduct further paleontological research elucidating the precise chronostratigraphic position of those objects that have reliable isotope–geochronologic age substantiation, but insufficiently strict allocation in the GSS. The second and main course is to select new reference objects, the age determination of which would help solve the problem, to reliably date them, and also to study further the geochronology of the objects, the results of which are still unreliable.

The realization of both courses in the calibration of the scale or its separate parts should be carried out by coordinated and consistent efforts of stratigraphers, paleontologists, and geochronologists within combined programs. To obtain the universal PGTS, the programs should be international. This does not exclude, but rather implies realization of regional (national) programs of calibrating corresponding scales. The latter are necessary not only because they are parts of the general scale, as likewise postulated by Odin (1994) in regard to the GSS. The regional or national PGTS are required for geological mapping and compilation of legends, because in most cases it is rather complicated to carry out a direct correlation of the local and regional stratigraphic units with the Global Stratotype Sections and Points (GSSP). Furthermore, calibration of the regional (national) PGTS will contribute to the progress in the realization of the GSSP concept, because now, by Odin's data (Odin, 1994), only 18 boundaries of the main GSS units are determined in accordance with the requirements of this concept.

Besides general requirements, the selection of boundary stratotypes of the GSS units should comply with the possibility of dating the boundary by isotopic geochronology. This means that in the actual vicinity of the boundary, or on both sides of it, there should be objects, the ages of which can be determined with isotopic methods (volcanites, bentonites, etc.). The satisfaction of these requirements will encourage both the PGTS calibration and correlation of any local and regional stratigraphic units with the GSS, if they contain rocks, the isotope age of which can be determined, whereas paleontological data do not ensure the uniqueness of this correlation.

I consider the creation of the national, Russian PGTS extremely urgent and important. Beyond purely scientific purposes, it will help to realize the compilation of a new generation of the State Geological Map (SGM) of Russia in scales 1 : 200 000 and 1 : 1 000 000. Without the PGTS, adopted as an obligatory document, it is difficult to unify legends, particularly for magmatic rocks, and to effectively apply numerous reliable isotope dating for improvement and greater informative capacity of the new SGM generation. Moreover, it should be taken into account that at present only a few objects in Russia are dated as reference points for the scale of this country.

The possibility of calibrating the national scale is provided primarily by numerous volcanogenic formations on the territory of Russia, which are different in age and have sufficiently reliable chronostratigraphic allocations. As far as I am aware, these are the Cambrian and Devonian volcanites in the Altai–Sayan area, the Silurian and Permian volcanic rocks of the Urals, the Permian–Triassic volcanites in the north of the Siberian platform, the Mesozoic–Cenozoic formations of the Far East, Northeastern and Transbaikalia regions. By improving analytical capacities of our laboratories, the list of reference objects can be amplified by using bentonites. The advantages of international cooperation should likewise be applied for the benefit of this research.

I sincerely hope that the problems described in this paper will draw the attention of the geological community to this field of study, which was practically neglected in Russia for the last twenty years.

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