CHRONOS—Integrated Stratigraphic Databases, the Development of an International Standard Time Scale and the Interoperability with Time Scales of U.S. State Surveys

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INTRODUCTION

Modern Earth system history research increasingly depends upon the analysis of voluminous multidisciplinary, time-calibrated data. The process of determining the availability or even the existence of Earth history data remains a time-consuming and error-prone enterprise because there are no centralized depositories or Web-enabled means for locating and retrieving data. The goal of CHRONOS is to unify current and future stratigraphic databases into a powerful system for producing a dynamic global time scale for Earth history and for understanding the complex relationships of past geologic, climatic and evolutionary trends. Web-services and an extensive on-line suite of toolboxes will allow global researchers and the general public to access, analyze and visualize CHRONOS stratigraphic information. Another goal, and the centerpiece of the CHRONOS system, is a vastly improved high-resolution geological time scale.

A logical series of tasks is planned to accomplish these goals, with the ultimate goal being for all geoscientists to be able to apply the CHRONOS system of integrated databases for deciphering the complex interactions of the Earth system through all of geologic time. In addition to its primary goals of enabling networking of international databases and facilitating creative research, the CHRONOS outreach programs will promote education of Earth's fascinating history.

CHRONOS is a system within the larger effort of the National Science Foundation for cyberinfrastructure in the earth sciences (called Geoinformatics). It will be a distributed system with a single portal at a central hub that will provide information technology expertise and tools and link the various thematic nodes or networks, projects, and databases constituting CHRONOS (fig. 1).

The implementation of CHRONOS will involve the following tasks:

- Progressively establish and interlink critical thematic database networks for life through time, radiometric age, climate through time, chemical and sedimentary cycles through time, core-to-crust dynamics through time (such as magnetostratigraphy), and other components of Earth system history;
- Establish central CHRONOS portal to access and analyze major component data types for researchers and the general public;
- Develop advanced tools and visualization capabilities that investigators can apply to uploaded data in their on space on a CHRONOS server or download to their own system;
- Assemble a high-precision 'Standard Geological Time Scale' under the aegis of the International Commission on Stratigraphy;
- Coordinate an outreach program with educational modules and informative demonstrations of the CHRONOS system; and
- Study four critical time-slices of Earth history as 'test-bed' investigations, using the expanding capabilities of the information-technology infrastructure and toolkits of the assembled CHRONOS system.

The four time-slice studies address longstanding scientific questions of societal relevance and interest (Cambrian life explosion, Permian-Triassic catastrophic extinctions, middle Cretaceous super-greenhouse world, and middle Miocene climate transitions; see fig. 2). Each involves different types and qualities of data and will improve and refine marine and continental data cor-

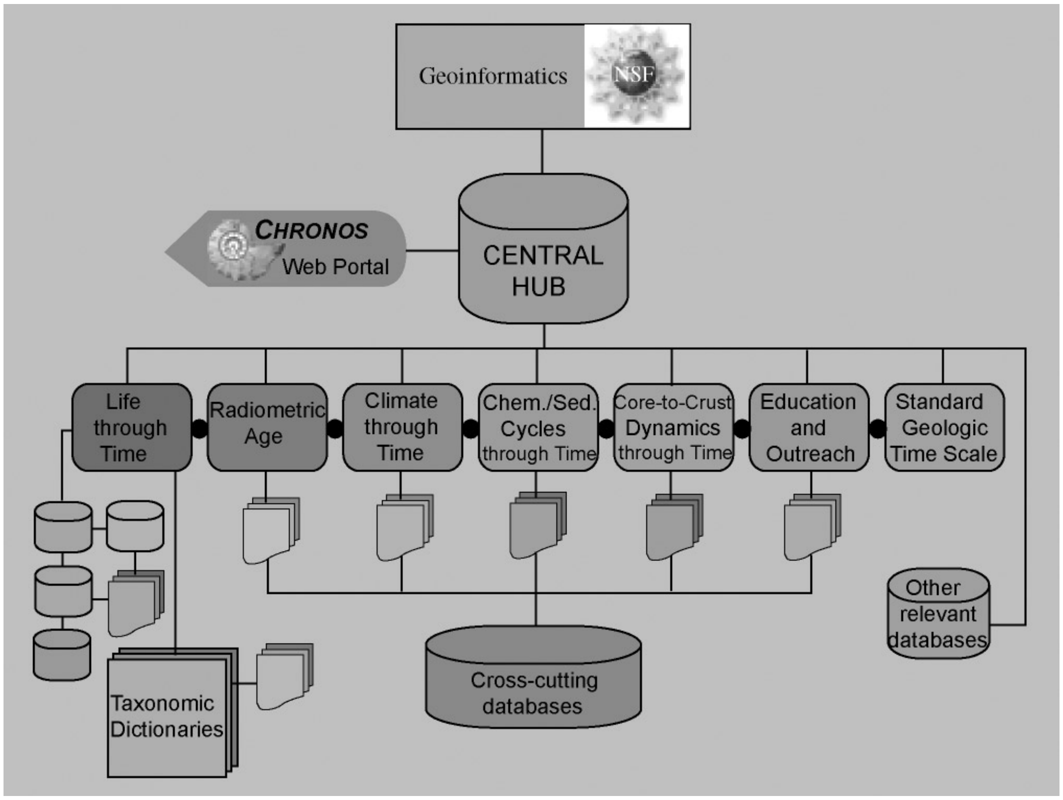

Figure 1. Schematic of the distributed CHRONOS system.

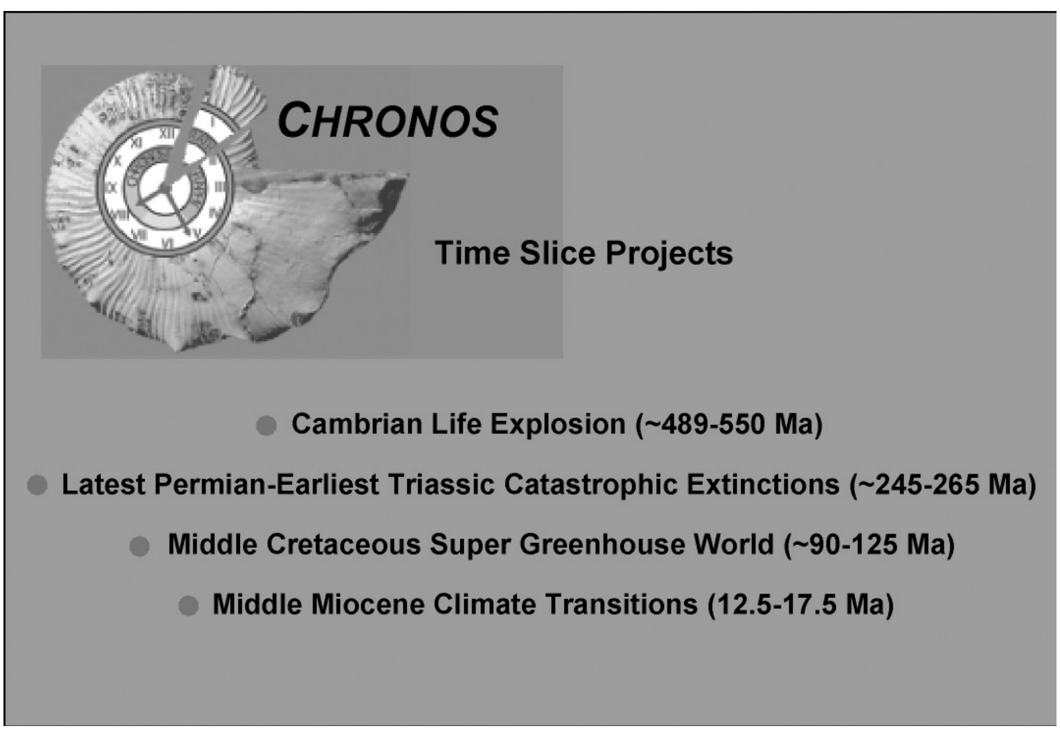

Figure 2. Time Slice Projects of CHRONOS.

relations at the global scale. The ultimate goal is for all geoscientists to be able to apply the CHRONOS system of integrated databases for deciphering the complex interactions of the Earth system through all of geologic time.

HOW THE CHRONOS INTERACTIVE NETWORK WILL WORK WITH DMT AND THE U.S STATE SURVEYS

An example of how CHRONOS will support the goals of the Digital Mapping Techniques workshops is the seamless way it will relate local state geological survey time scales to the International Time Scale. Initial information and links for both local and international scales will be available from the National Geologic Map Database's Geological Names Lexicon ("GEOLEX", http://ngmsvr.wr.usgs.gov/Geolex/). The current international scale is available from the International Commission on Stratigraphy (ICS, http://www.micropress.org/stratigraphy/index.htm) or a slightly modified version (retaining the Tertiary) from the U. S. Geological Survey (USGS), soon to be available on GEOLEX (fig. 3).

As an example of how CHRONOS will function, let us imagine that we want to know where the currently internationally-defined Carboniferous-Permian boundary falls in the sections in Kansas and West Texas and how it relates to the boundary recognized by those states. From the CHRONOS portal, you would be linked to the ICS site containing the Global Stratotype Section and Points (GSSP's) for all formally accepted boundaries of the ICS (currently, go to http://www.micropress.org/stratigraphy/index.htm, and select "GSSP's"). The Carboniferous-Permian boundary information displayed is as follows:

The first box leads to: http://www.micropress.org/stratigraphy/carper.htm where we find full references and section and map; the *Episodes* article also is available digitally.

From a completely different source identified by CHRONOS, we would get a current reinterpretation of the conodont lineages from the GSSP (http://www.kgs.ukans.edu/, fig. 4), as found in Wardlaw and others (2003). From the same publication, the conodont ranges from Kansas are shown (fig. 5). A brief history of the placement of the Permian boundary in Kansas would be available from Paleodata (the National Geologic Map Database's National Paleontologic Database, fig. 6) which will show where R. C. Moore placed the boundary at the top of the Brownville Limestone, which became the "traditional" boundary; and where the boundary was modified using the first occurrence of the *Streptognathodus constrictus* conodont zone (an early contender for the boundary definition) placed by Baars and others (1994) at the base of the Neva Limestone. However, Boardman and others (1998) clearly show the first occurrence of *S. constrictus* and other species that make up the zone in the underlying Burr Limestone. The first occurrence of *S. isolatus* (the international boundary indicator) is in the Bennett Shale of the Red Eagle Limestone.

Further, in the reference section for the Carboniferous-Permian boundary at Usolka in the Urals, Russia, there are found volcanic tuffs centimeters below and above the first occurrence of *Streptognathodus isolatus* that yield abundant zircons (*Permophiles* no. 39, http://pri.boisestate.edu/permophiles/issue39.pdf). Both horizons indicate virtually the same date, and though preliminary, are dated at 299 million years before present(Ma). This provides a solid age that can be applied to both Kansas and West Texas sections. Again, from the ICS

base Asselian Stage, base Cisuralian Series, base Permian System	Conodont, lowest occurrence of *Streptognathodus isolatus* within the *S. "wabaunsensis"* conodont chronocline. 6 m higher is lowest fusilinid foraminifer *Sphaeroschwagerina*	27 m above base of Bed 19, Aidaralash Creek, Aktöbe, southern Ural Mountains, northern Kazakhstan	Ratified, 1996	Episodes 21 (1), p.11

INTERNATIONAL STRATIGRAPHIC CHART

International Union of Geological Sciences

Commission de la Carte Geologique du Monde
Commission on the Geological Map of the World

International Commission on Stratigraphy

http://www.micropress.org/stratigraphy/

As Modified by

EONOTHEM EON	ERATHEM ERA	SYSTEM PERIOD	SERIES EPOCH	STAGE AGE	AGE Ma	SEPM Spec. Vol. #54 (1995) +/-		STAGE NOTATION	SERIES NOTATION	SYSTEM NOTATION
PHANEROZOIC PH	CENOZOIC CZ	Quaternary	HOLOCENE		0.01				Q_2	Q
			PLEISTOCENE	Calabrian	1.81		GSSP		Q_1	
	TERTIARY	NEOGENE	PLIOCENE	Gelasian	2.58		GSSP	n9	N_2	N
				Piacenzian	3.60		GSSP	n8		
				Zanclean	5.32		GSSP	n7		
			MIOCENE	Messinian	7.12		GSSP	n6	N_1	
				Tortonian	11.2			n5		
				Serravallian	14.8			n4		
				Langhian	16.4			n3		
				Burdigalian	20.5			n2		
				Aquitanian	23.8		GSSP	n1		
		PALEOGENE	OLIGOCENE	Chattian	28.5			e9	E_3	E
				Rupelian	33.7		GSSP	e8		
			EOCENE	Priabonian	37.0			e7	E_2	
				Bartonian	41.3			e6		
				Lutetian	49.0			e5		
				Ypresian	55.0			e4		
			PALEOCENE	Thanetian	57.9			e3	E_1	
				Selandian	61.0			e2		
				Danian	65.5	0.1	GSSP	e1		
	MESOZOIC MZ	CRETACEOUS	UPPER/LATE	Maastrichtian	71.3	0.5	GSSP	k6	K_2	K
				Campanian	83.5	0.5		k5		
				Santonian	85.8	0.5		k4		
				Coniacian	89.0	0.5		k3		
				Turonian	93.5	0.2		k2		
				Cenomanian	98.9	0.6	GSSP	k1		
			LOWER/EARLY	Albian	112.2	1.1		b6	K_1	
				Aptian	121.0	1.4		b5		
				Barremian	127.0	1.6		b4		
				Hauterivian	132.0	1.9		b3		
				Valanginian	136.5	2.2		b2		
				Berriasian	142.0	2.6		b1		
		JURASSIC	UPPER/LATE	Tithonian	150.7	3.0		j7	J_3	J
				Kimmeridgian	154.1	3.3		j6		
				Oxfordian	159.4	3.6		j5		
			MIDDLE	Callovian	164.4	3.8		j4	J_2	
				Bathonian	169.2	4.0		j3		
				Bajocian	176.5	4.0	GSSP	j2		
				Aalenian	180.1	4.0	GSSP	j1		
			LOWER/EARLY	Toarcian	189.6	4.0		l4	J_1	
				Pliensbachian	195.3	3.9		l3		
				Sinemurian	201.9	3.9	GSSP	l2		
				Hettangian	205.1	4.0		l1		
		TRIASSIC	UPPER/LATE	Rhaetian	209.6	4.1		t7	T_3	T
				Norian	220.7	4.4		t6		
				Carnian	227.4	4.5		t5		
			MIDDLE	Ladinian	234.3	4.6		t4	T_2	
				Anisian	241.7	4.7		t3		
			LOWER/EARLY	Olenekian	244.8	4.8		t2	T_1	
				Induan	250	4.8	GSSP	t1		

EONOTHEM EON	ERATHEM ERA	SYSTEM PERIOD	SERIES EPOCH	STAGE AGE	AGE Ma	Subcommissions or other sources +/-		STAGE NOTATION	SERIES NOTATION	SYSTEM NOTATION
PHANEROZOIC PH	PALEOZOIC PZ	PERMIAN			251.4	3.6				
			LOPINGIAN	Changhsingian	253.4			p9	P_3	P
				Wuchiapingian				p8		
			GUADALUPIAN	Capitanian	265		GSSP	p7	P_2	
				Wordian			GSSP	p6		
				Roadian			GSSP	p5		
			CISURALIAN	Kungurian				p4	P_1	
				Artinskian				p3		
				Sakmarian	283			p2		
				Asselian	292		GSSP	p1		
		CARBONIFEROUS	PENNSYLVANIAN	Gzhelian				c7	C_2	C
				Kazimovian				c6		
				Moscovian				c5		
				Bashkirian	320		GSSP	c4		
			MISSISSIPPIAN	Serpukhovian	327			c3	C_1	
				Visean	342	3.6		c2		
				Tournaisian	354	4	GSSP	c1		
		DEVONIAN	UPPER/LATE	Famennian	364		GSSP	d7	D_3	D
				Frasnian	370		GSSP	d6		
			MIDDLE	Givetian	380		GSSP	d5	D_2	
				Eifelian	391		GSSP	d4		
			LOWER/EARLY	Emsian	400		GSSP	d3	D_1	
				Pragian	412		GSSP	d2		
				Lochkovian	417		GSSP	d1		
		SILURIAN	PRIDOLI		419		GSSP	s8	S_4	S
			LUDLOW	Ludfordian			GSSP	s7	S_3	
				Gorstian	423		GSSP	s6		
			WENLOCK	Homerian			GSSP	s4	S_2	
				Sheinwoodian	428		GSSP	s5		
			LLANDOVERY	Telychian			GSSP	s3	S_1	
				Aeronian			GSSP	s2		
				Rhuddanian	440		GSSP	s1		
		ORDOVICIAN	UPPER/LATE	"sixth stage"					O_3	O
				"fifth stage"			GSSP			
			MIDDLE	Darriwillian	467.5	3	GSSP		O_2	
				"third stage"						
			LOWER/EARLY	"second stage"			GSSP		O_1	
				Tremadocian	495		GSSP			
		CAMBRIAN	UPPER/LATE		500				$Є_3$	Є
			MIDDLE		520				$Є_2$	
			LOWER/EARLY		545		GSSP		$Є_1$	

EON	ERA	SYSTEM PERIOD	AGE Ma		SERIES NOTATION	SYSTEM NOTATION
PRECAMBRIAN PЄ			540			ERA
	PROTEROZOIC PR: NEOPROTEROZOIC	NEOPROTEROZOIC III	650	GSSA	NP_3	NP
		CRYOGENIAN	850	GSSA	NP_2	
		TONIAN	1000	GSSA	NP_1	
	MESOPROTEROZOIC	STENIAN	1200	GSSA	MP_3	MP
		ECTASIAN	1400	GSSA	MP_2	
		CALYMMIAN	1600	GSSA	MP_1	
	PALEOPROTEROZOIC	STATHERIAN	1800	GSSA	PP_4	PP
		OROSIRIAN	2050	GSSA	PP_3	
		RHYACIAN	2300	GSSA	PP_2	
		SIDERIAN	2500	GSSA	PP_1	
	ARCHEAN AR: NEOARCHEAN	No subdivision into periods	2800			NA
	MESOARCHEAN		3200			MA
	PALEOARCHEAN		3600			PA
	EOARCHEAN					EA

Figure 3. International Stratigraphic Chart as modified by USGS.

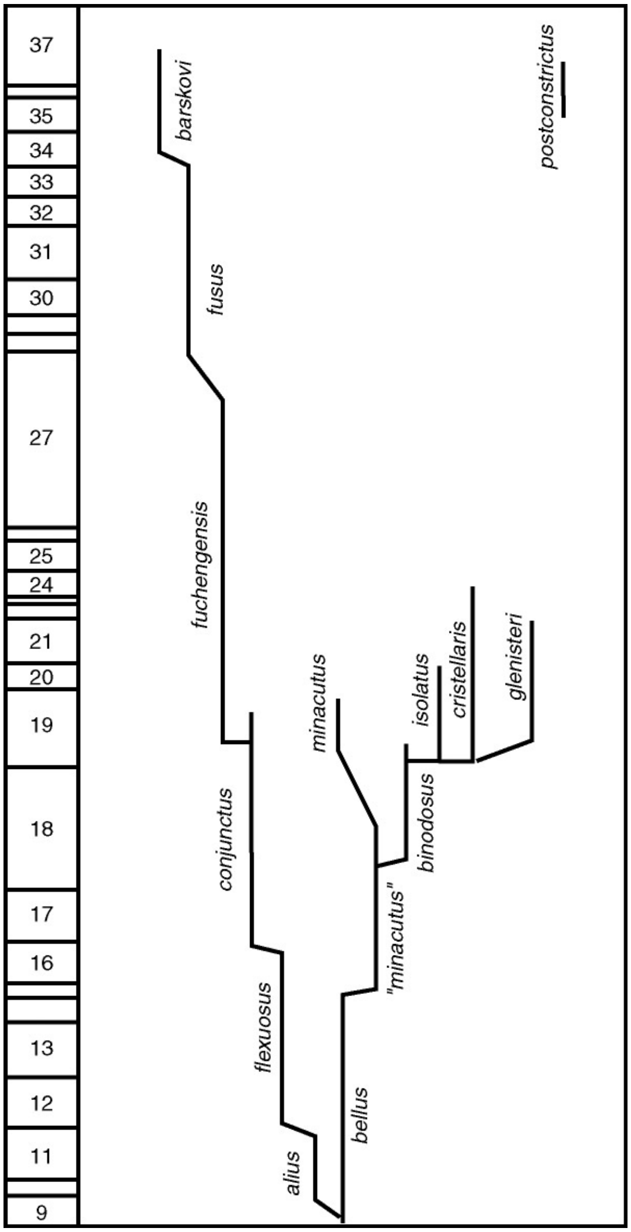

Figure 4. Interpretation of *Streptognathodus* conodont lineages from the GSSP of the Permian at Aidaralash Creek, Kazakhstan; section shown as numbered beds (from Wardlaw and others, 2003).

website, information on relevant radiometric dates utilized in constructing the Phanerozoic time scale is available (fig. 7, from Gradstein and Ogg, 2004, to be made available through ICS).

For the necessary stratigraphic information for West Texas, we would be linked to a digital copy of an article from *Permophiles* issue number 36 (June, 2000, http://pri.boisestate.edu/permophiles/issue36.pdf) which follows:

"Preliminary Placement of the International Permian Working Standard to the Glass Mountains, Texas"

Bruce R. Wardlaw, U.S. Geological Survey, Reston, VA
Vladimir I. Davydov, Permian Research Institute, Boise State Univ., Boise, ID

The International Lower Permian Working Standard is based on the conodont distributions in the southern Urals, Kansas, and West Texas. Asselian is defined on the first appearance of *Streptognathodus isolatus*. This occurs at the base of the Bennett Shale of the Red Eagle Limestone in Kansas. The current working definition for the base of the Sakmarian is the First Appearance (FA) of *Streptognathodus barskovi (sensu strictu)*. This occurs in the Eiss Limestone of the Bader Limestone in Kansas and is very close to the FA of *Sweetognathus merrilli* in the upper part of the Eiss. The working definition of the base of the Artinskian is the FA of *S. florensis* or *Sweetognthus whitei,* which both first appear in the base of the Florence Limestone of the Barnston Formation in Kansas. After Barneston deposition the Kansas section remains very shallow during marine incursions and only sparse to common *Sweetognathus* or *Rabegnathus* faunas are recovered. The working standard for Kungurian conodont zonation is based on the distribution of conodonts from the Glass Mountains, Texas. The working definition of the base of the Kungurian is the FA of *Neostreptognathodus "exsculptus"*.

The Grey Limestone Member of the Gaptank Formation is a shallow-water carbonate that forms the top of the formation. Conodont faunas are sparse, but the base of the Grey Limestone Member contains a conodont fauna that correlates to the Foraker Limestone with the overlap of the ending range of *Streptognathodus brownvillensis* and *S. elongatus*. The top of the Grey Limestone contains a conodont fauna that correlates to the Grenola Limestone with *Streptognathodus nevaensis* and *S. elongatus*. Therefore, the Carboniferous-Permian boundary is located within the Grey Limestone.

First Appearance of	Stratigraphic Position
N. "exsculptus"	17 m above base, Skinner Ranch Formation
S. barskovi	52 m above base, Neal Ranch Formation
S. nevaensis	Top of Grey Limestone Member
S. elongatus	Base of Grey Limestone Member

The Neal Ranch Formation is dominated by prodelta siltstones with common plant debris and limestone and limestone conglomerate interbeds. The limestones yield a fair conodont fauna. At 52 m above the base *Streptognathodus barskovi, S. isolatus* and *Sweetongnathus merrilli* occur (equivalent to bed 12 of Ross, 1963). The overlap of *barskovi* and *isolatus* indicates the base of the *S. barskovi* zone. *Streptognathodus barskovi* occurs higher at 71 m where it occurs with *S. postconstrictus* which indicates the upper part of its zone.

The Lenox Hills Formation is largely delta conglomerates and does not yield conodonts. However, in the Dugout Mountain area, it contains common limestone which yields a sparse fauna of *Sweetognathus whitei* and *Neostreptognathodus transitus*. This fauna indicates the upper Artinskian. Conodonts do not well constrain the Sakmarian-Artinskian boundary.

The Skinner Ranch formation is largely limestone and limestone conglomerate with abundant conodont fuanas. In its type section it contains *Neostreptognathodus pequopensis* at its base. At 17 m, a plethora of species of *Mesogondolella* and *Streptognathodus* occur, including *Neostreptognathodus "exsculptus"* which marks the base of the Kungurian."

Since publication of that article, the working definitions have been refined and changed to formal proposals, and the definition of the Sakmarian has changed from the First Appearance Datum (FAD) of *Streptognathodus barskovi* to the FAD of *Sweetognathus merrilli* (*Permophiles* no. 41, http://pri.boisestate.edu/permophiles/issue41.pdf)

We want more substantial information, so CHRONOS would conduct an author search for Wardlaw and for Davydov, and find that there is no further information published by these authors on the placement of conodonts in the lower part of the West Texas regional stratotype. However, in our author search, we find all of Wardlaw's field information is available via PaleoStrat (https://www.paleostrat.com), a paleontologic and stratigraphic information system that allows us to see the measured section (fig. 8), information on each sample, and the conodont faunas recovered and digital images of the representative specimens. Thus, we are assured of the placement of the Carboniferous-Permian boundary in the Wolfcamp Hills/Geologist Canyon section, the regional stratotype of the Wolfcampian.

CHRONOS will bring all this disparate information together for the user. The sources of information also will be accessible, so that additional ideas and questions can be posed by the user.

ACKNOWLEDGMENTS

Much of the description of CHRONOS comes from the interaction of the Steering Committee and their work on writing the NSF proposal (see http://www.CHRONOS.org). The author was only one of many participants and is indebted to all of CHRONOS' creators. The author is solely responsible for the time scale interpretations. I thank David Soller for a rigorous review of the article.

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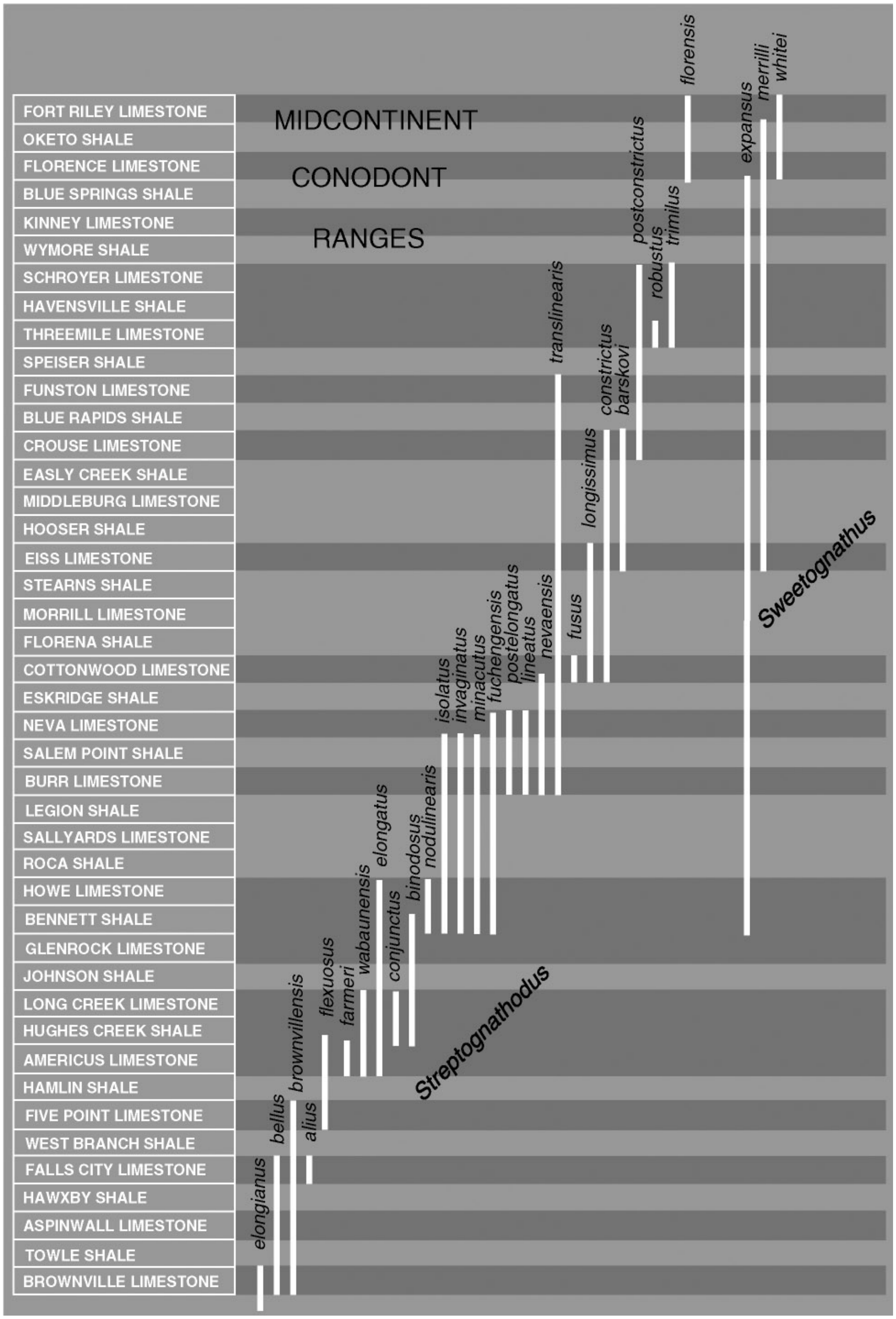

Figure 5. Ranges of conodont species in the Kansas section; darker intervals reflect largely marine deposition, lighter intervals reflect largely non- or marginal marine deposition (from Wardlaw and others, 2003).

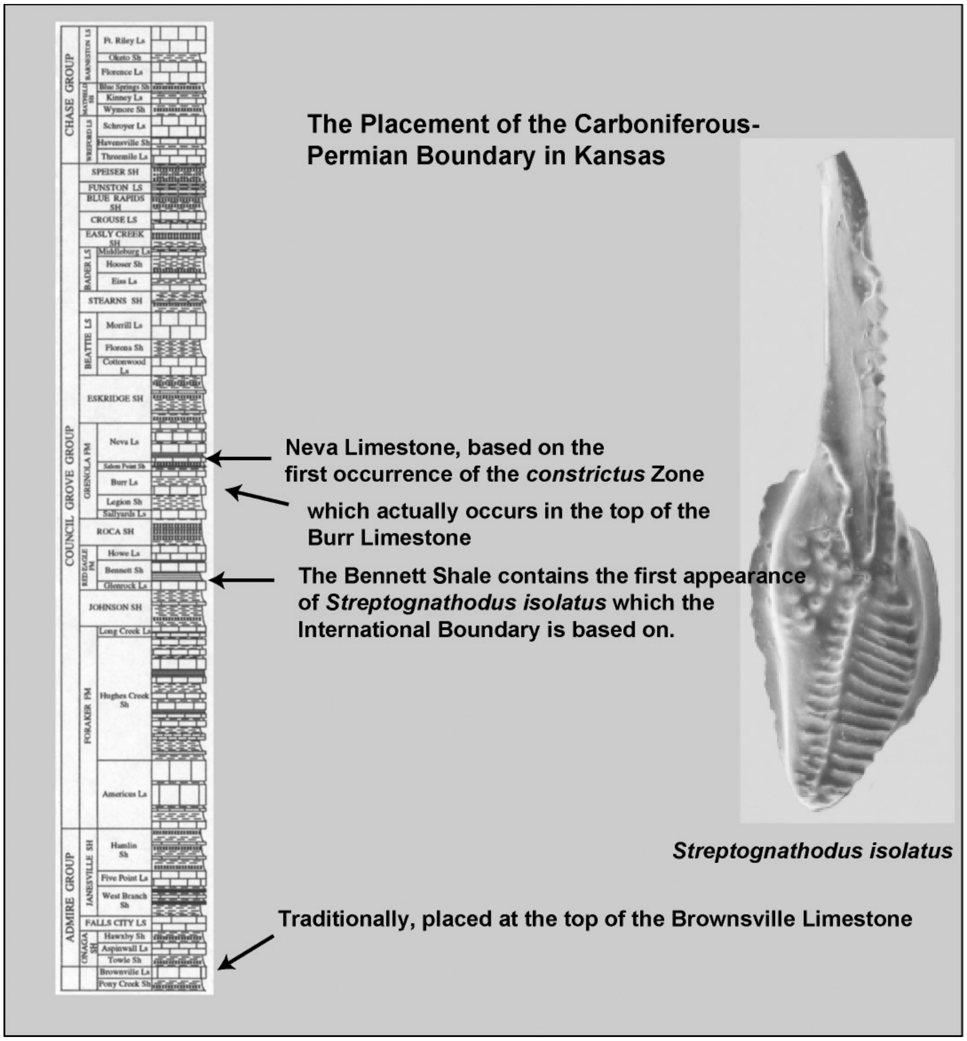

Figure 6. Historical Permian boundary placement in the Kansas section.

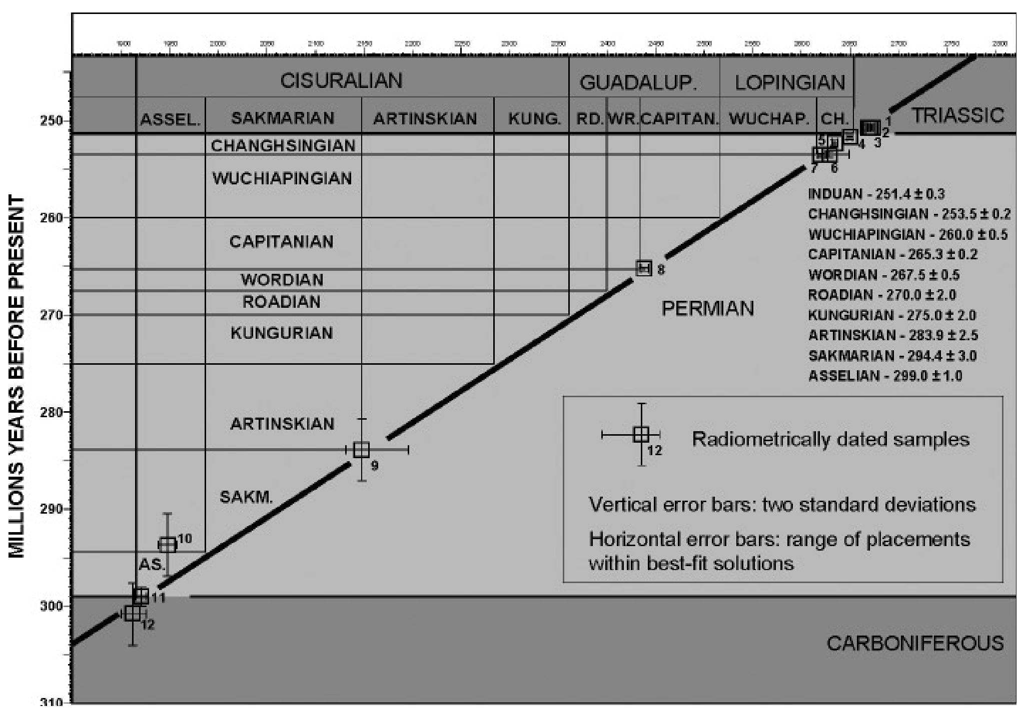

Figure 7. Graphical correlation of radiometric ages and stage boundaries of the Permian.

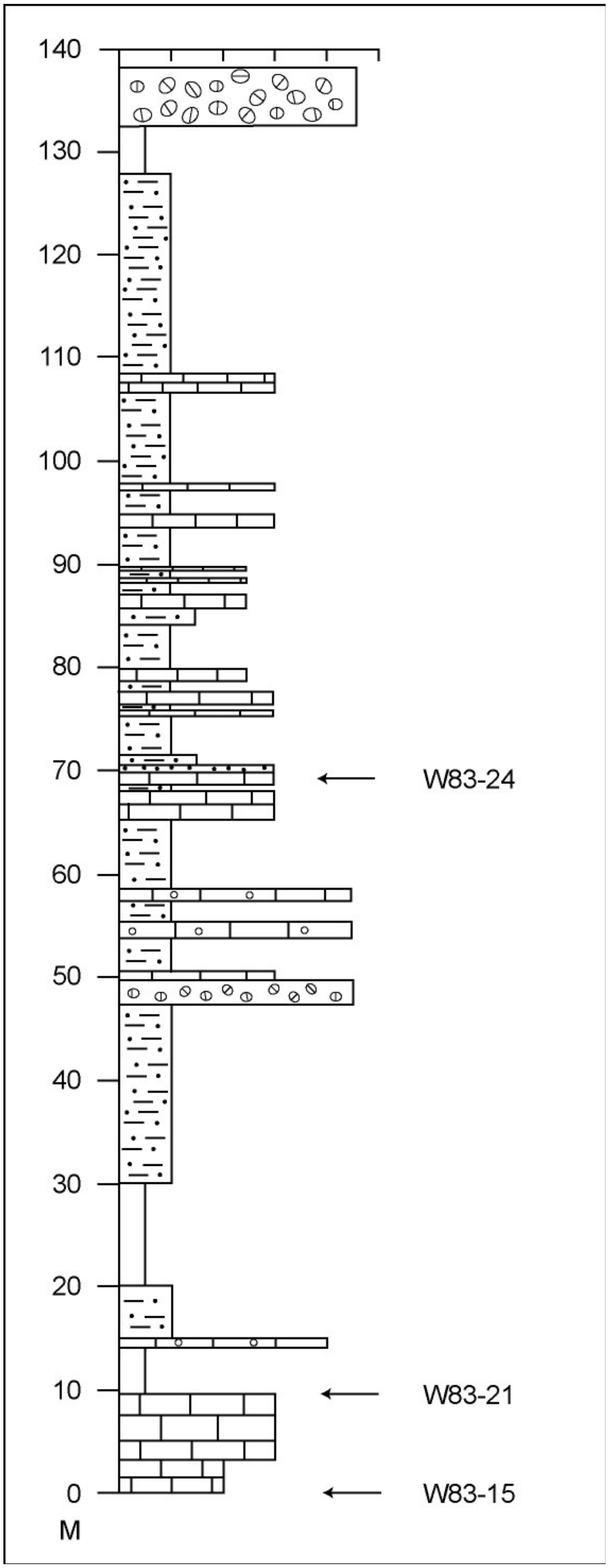

Figure 8. Columnar section of Wolfcamp Hills/Geologist Canyon section of Wardlaw and others (2003), and position of significant conodont samples. Measured in 1983 and recollected in 1984 (from PaleoStrat, definition of horizontal scale based on grain size also in PaleoStrat).